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Adaptation to climate change effects and competition between ports: Invest now or later?

Laingo M. Randrianarisoa[1,*], Anming Zhang

Sauder School of Business, University of British Columbia, Canada

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A B S T R A C T

We investigate the size and timing of investment in adaptation to climate change effects for ports, when efficiency of investment is uncertain and the market is competitive. We develop a two-period real options game model with two "landlord" ports, each consisting of a port authority (PA) and a downstream terminal operator company (TOC). The two PAs compete with each other at the upstream level, and the two TOCs downstream. The model assumes an accumulation of information about the adaptation projects over time, allowing decision-makers to improve the investment efficiency. The results show that the optimal timing of investment is significantly influenced by the disaster occurrence probability, the potential information gain over time and the level of competition. When competition is intensified, it is optimal for ports to invest earlier than later. However, immediate investments are less preferred when competition is weak, even lesser in the presence of information accumulation. Waiting until the next period to invest is also a better option if the disaster occurrence probability is low or if the shippers' expected disaster losses are negligible. Moreover, information accumulation reduces the ports' investment size, while improving the discounted welfare associated with late investments. These results hold for both the private and public ports and for simultaneous investments by the PAs. In most cases, social welfare is much higher with immediate investments, mainly because of the associated positive spillover effects on the surrounding areas and other sectors of economy. The implications of the assumption of Knightian uncertainty for the disaster occurrence probability are discussed.

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1. Introduction

This paper deals with a topic widely recognized as important in the recent years, namely the optimal size and timing of investment in adaptation to climate change effects for transportation facilities under uncertainty in a competitive market. The impacts of climate change on transportation facilities and regional economies have become more and more significant,

* Corresponding author.
E-mail addresses: laingo.randrianarisoa@sauder.ubc.ca (L.M. Randrianarisoa), anming.zhang@sauder.ubc.ca (A. Zhang).

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considering the relevance of the change in patterns and frequencies of extreme weather and natural disasters. Scientific studies suggest that climate change likely leads to an increase in occurrence/frequency or strength of weather-related natural disasters (e.g. Keohane and Victor, 2011; Min et al., 2011; OECD, 2016),[2] and its effects can be severe and devastating for the economy (see, among others, Belasen and Polachek (2008, 2009) for the impacts of hurricanes on the labor market; Hallstrom and Smith (2005) on the housing prices; Auffret (2003) on consumption and aggregate welfare; Xiao (2011) on local economy, and Altay and Ramirez (2010) on supply chains in different sectors). According to the latest data from National Centers for Environmental Information (NCEI), year 2017 tied an all-time record in the most billion-dollars[3] disasters in the US. Moreover, the US experienced 16 separate billion-dollar weather and climate disasters, which collectively claimed 282 deaths and led to significant economic effects on the areas impacted during the first ten months of 2017 (NOAA, 2018).[4]

In this paper, we investigate the investment decisions of ports when it comes to climate change adaptation under uncertainty in a competitive environment. Evidence shows that climate change effects have caused substantial financial damage costs to the ports.[5] Due to their coastal location, seaports and terminals (such as transport infra- and super-structures, utilities and equipment) are vulnerable to extreme weather and coastal and marine natural disasters, such as hurricane, storm surge, earthquake and flooding (OECD, 2016), as well as long-run sea-level rise (SLR).[6] In the aftermath of a disaster, the port activities are extensively disrupted. In most cases, the port facilities are shut down for several days. For example, Port of New York/ New Jersey was closed for several days following Hurricane Sandy (Smythe, 2013). Hurricane Harvey left Port of Houston, port facilities in Galveston, Corpus Christi, and elsewhere along the coast closed for several days in 2017, resulting in serious delays in cargo delivery. Port of Busan in South Korea was shut down for 91 days after 2013 Typhoon Maemi (Lam et al., 2017) and Port of Sendai for 36 days after the 2011 Earthquake and Tsunami in Japan.[7] Besides, natural disasters feature among the main causes of port disruptions in Asia (Lam and Su, 2015). Furthermore, port disruptions caused by major damage from natural disasters can lead to significant short-term reduction in port revenue and long-term loss of traffic to other coastal and world ports (Chang, 2000; Friedt, 2018).[8] They generate major economic losses with a long lasting impact (Chang, 2000; Paul and Maloni, 2010; Berle et al., 2011). Most importantly, since more than 80% of globally traded goods (by weight) are transported by sea (Ng and Liu, 2014), the impacts are not limited to the ports themselves, but extend to the entire transportation system, trade and regional economy.

The severity of the consequences of climate change calls for efficient and timely investment in disaster prevention transportation facilities. However, the choice of investment timing remains a big challenge for the port authorities. On one hand, they may decide to invest as early as possible to protect the port infrastructures and related assets in the event of disasters, while improving their competitive position over time. On the other hand, given the uncertainties of the return on investment, the decision-makers may face a trade-off between investing in disaster prevention facilities and promoting businesses and port activities. Until recently, the ports' immediate concerns were focused on upgrading the facilities so as to keep up with the increase in shipping traffic and relieving the pressure from shippers, who experience serious delays at the ports.[9] As a consequence, there is no clear-cut answer regarding the timing of port adaptation in a competitive environment. Understanding the optimal timing of adaptation investment has broad implications for the entire transport network and regional economy, having nearby infrastructure with high resiliency provides backup facilities when one infrastructure becomes unavailable as a result of disaster (Itoh, 2018). In practice, approximately 3.2% of international seaports have planned to build protective structures in 2012, while 22% had no plans to develop adaptation and resiliency plans within the next 10 years (Becker et al., 2012). An extensive survey by the authors in 2017 suggests that 9 out of 48 major US container ports have adopted resiliency plans and implemented adaptation strategies.[10] Japanese ports, however, have taken disaster adaptation very seriously for a long time.[11]

[2] Nicholls et al. (2008) assess the exposure to flooding for 136 large port cities around the globe.

[3] Unless otherwise indicated, we use term 'dollars' for 'US dollars' throughout the paper.

[4] These disasters include floods in California, Missouri and Arkansas, tropical cyclones (Hurricane Harvey, Irma and Maria) in coastal areas, severe storms in Colorado, Minnesota, Midwest, Central and South/Southeast, extreme drought in North Dakota, wildfire in the West, freeze in Southeast, and tornados in Midwest, Central, Southeast and South.

[5] Among others, Hurricane Katrina caused damage costs amounted to $99.9 million to the Gulf ports in 2005 (PEER, 2006), $1.7 billion to southern Louisiana ports and over 200 onshore releases of hazardous chemicals or petroleum products (Santella et al., 2010). The total losses from Hurricane Ike to waterways, coastlines and Texas ports are estimated at $2.4 billion (FEMA, 2008).

[6] IPCC (2013) estimated a range from 0.18 to 0.59 meter of SLR for 2100, while other estimates extend as high as 2 meters.

[7] Sendai, Hachinohe, Hitachinaka, Onahama, Ishinomaki, Ofunato, Kashima are among the ports damaged by Earthquake and Tsunami in Japan in 2011.

[8] Chang (2000) found that Port of Kobe (Japan) experienced a decrease in regional and international container traffic after the 1995 Great Hanshin earthquake, while its rivals improved their competitive position. Friedt (2018) showed that ports that are directly affected by Hurricane Katrina exhibit reductions in trade (in terms of both trade value and number of traded products) while the nearest neighbouring ports experience substantial increase in trade.

[9] This has been the case of Gulfport, which adopted a plan to elevate the entire port from 10 to 25 feet in the aftermath of Hurricane Katrina so as to improve the port's resilience. However, as new information became available over time, Gulfport revised its decision and redirected the restoration funds to channel dredging projects. This decision was primarily motivated by the need for promoting businesses and competition (Becker et al., 2015).

[10] Among others, the Port of Seattle's philosophy is premised on the bet that significant SLR will not occur until about 50 years from now. This results in replacement of assets at the end of their lifespan and elevation (theoretically) before SLR would inundate them. Rhode Island also argued that it's better to leave room to erect future seawall and other defences.

[11] For example, Tokyo port is well equipped with earthquake resistant quays to counter earthquakes (Port of Tokyo, 2009).

We propose a two-period real options game model to investigate the investment decisions of ports under uncertainty in a competitive market. Specifically, we analyze whether the decision-makers should invest in port adaptation to climate change effects immediately or wait until the next period, when the environment is competitive, efficiency of investment is uncertain, and when information accumulation between periods matters. To the best of our knowledge, this study is the first to attempt to analyze transportation investment under uncertainty, by incorporating information accumulation and dynamic competition between ports into a real options game model. The model framework considers two "landlord" ports, each consisting of a port authority (PA) and a downstream terminal operator company (TOC). The two PAs compete with each other at the upstream level in each period, and the two TOCs downstream. The PAs make investment decisions at the beginning of either the first or the second period. If the investments are made early, the port facilities and shippers' assets are protected from disasters for the two periods. Otherwise, they will incur the maximum possible damage if a disaster happens during the first period. Efficiency of investment is assumed to be uncertain in both periods, but the ports acquire more information and better knowledge of the potential disaster events and adaptation projects in the second period. This information gain is translated into a positive change in investment efficiency between the periods. In terms of probability, the distribution of the investment efficiency in the second period is as large as its distribution in the first period in the sense of *First-degree Stochastic Dominance (FSD)*.

This study is related to two strands of literature: (i) on modeling seaport adaptation investment under uncertainty and (ii) on using real options game models for transport infrastructure investment. Most studies on adaptation to climate change effects for ports are either descriptive or qualitative (Esteban et al., 2009; Nicholls et al., 2010; Becker et al., 2012; Becker et al., 2013; Ng et al., 2013; Becker et al., 2015; Ng et al., 2015; OECD, 2016; Becker et al., 2018).[12] A few studies (Xiao et al. 2015; Wang and Zhang 2018) have modeled ports' adaptation investments under uncertainty. Xiao et al. (2015) developed a two-period economic model in which the ports simultaneously choose disaster prevention investments so as to minimize discounted costs. Their model considers uncertainty of the disaster occurrence probability, and assumes uniform distribution for this probability. Wang and Zhang (2018) extended Xiao et al. (2015)'s analytical framework to consider a wide family of probability distributions for the climate change-related disaster occurrence probability (Knightian uncertainty) and competition between ports. Wang and Zhang (2018) abstract away the issue of investment timing, while focusing on a single time period. The present study contributes to this line of research by analyzing the timing and size of adaptation investment in a model where dynamic competition between ports is taken into account.[13] Whilst the previous studies model uncertainty of disaster occurrence probability, we consider the uncertainties associated with the efficiency of adaptation investment. In practice, the sources of uncertainty matter when it comes to the decisions to invest in adaptation projects. In addition to the disaster occurrence probability, there are other important sources of uncertainty, including climate projections in scientific models, conflicting perspectives on the potential climate change effects, identification of the stakeholders and the most appropriate and effective adaptation measures, effective combination of near-term and long-range planning that includes hard and soft interventions (Ng et al., 2013), cost sharing arrangements and creation of new forms of collaboration between a wide set of public and private entities at the early stage of adaptation.[14] Considering the uncertainty of investment efficiency allows us to cover these multiple sources. In particular, we argue that better knowledge of one of these sources would help to improve the efficiency of adaptation investment, therefore influencing the timing decisions of the ports.

This research is also related to the extensive literature on modeling investment decisions in the context of uncertainty and competition or "*real options game models*".[15] Firms' investment strategies under uncertainty in a competitive setting are studied under the modeling framework of, among others, Williams (1993), Leahy (1993), Grenadier (2002), and Huisman and Kort (2015).[16] For example, Grenadier (2002) developed a tractable real options approach to derive the equilibrium investment strategies under uncertainty and determine the impact of competition in a continuous-time Cournot-Nash framework.

[12] Among the studies on adaptation to climate change effects, Mu et al. (2013) empirically examined US adaptation possibilities in terms of livestock and cropland use change and livestock stocking rate change. Chambwera et al. (2014) provided an assessment of the literature on the economics of climate change adaptation.

[13] The interaction between competition and investment decisions of facilities is well documented. See De Borger and Proost (2012) and Lee and Song (2017) for a comprehensive review of literature. In the maritime industry, De Borger et al. (2008), Zhang (2009), Wan and Zhang (2013) and Bae et al. (2013) analyze the pricing behaviour of competing ports, along with the optimal investment in port and hinterland capacity. See Wan et al. (2018) for a literature review. Research on duopolistic interaction between congestible facilities using a two-stage game includes Van Dender (2005), De Borger and Van Dender (2006), Zhang and Zhang (2006), Baake and Mitusch (2007) and Basso and Zhang (2007).

[14] For example, in the proposed terminal extension project, Port of Vancouver anticipated a rise of 0.5 meter by 2100 in the preliminary design. This assumption has been challenged by the Canada's federal environment department because it considers not much change in the waves and flooding storms, along with the absence of expected effects of SLR over the long term, though storm surge represents a major danger for the facilities (see McClearn (2018) for further details).

[15] There exist an extensive number of papers modelling investment decisions that consider uncertainty and competition. Azevedo and Paxson (2014) provide an extensive review of two decades of real options game models and their applications. Huisman et al. (2004) and Chevalier-Roignant et al. (2011) also review the literature on real options models, but their analyses are more centered on managerial insights concerning the nature of competitive advantage, the manner in which information is revealed, firm heterogeneity, capital increment size, and the number of competing firms. See also Grenadier (2000a) for a survey of the existing literature on game theory and real options approaches and Grenadier (2000b) for the illustrations of how the intersection of real options and game theory provides powerful new insights into the behaviour of economic agents under uncertainty.

[16] Studies combining real options valuation approach and game theory concepts in continuous time include, among others, Dixit and Pindyck (1994), Grenadier (1996), and Huisman (2013). Contributions to the discrete time framework are, among others, Smit and Ankum (1993) and Smit (2003). For example, Smit and Ankum (1993) develop a real options and game-theoretic approach to illustrate the influence of competition on project value and investment timing.

Huisman and Kort (2015) combined investment timing and capacity determination in a strategic real options model that accounts for competition between firms and optimal choice of capacity. A few studies have analyzed infrastructure and transportation investment under uncertainty. Xiao et al. (2013) analyzed the effects of demand uncertainty on airport capacity choice in a model where uncertain demand follows a continuous probability distribution. Chen et al. (2017) examined optimal facility investment of risk-averse governments and optimal pricing of risk-neutral ports under service differentiation and demand uncertainty. Chen and Liu (2016) developed a similar model, by considering risk-averse ports. Gao and Driouchi (2013) and Wang and Zhang (2018) investigated the impact of Knightian uncertainty in the transportation sector.[17] Gao and Driouchi (2013) focused on congestion relief value of a rail transit project, while Wang and Zhang (2018) addressed climate change adaptation for ports. Applications of real options game models to transportation investment include Smit (2003) and Balliaw et al. (2019).[18] Smit (2003) studied optimal airport infrastructure investment using a discrete-time options-game model in which airport growth opportunities and future cash-flow are uncertain, and Balliauw et al. (2019) examined the investment timing and capacity choice decisions of ports in a continuous-time real options model under quantity competition and uncertain demand.

Our paper differs from the previous studies on transportation investment under uncertainty in three respects. First, unlike Smit (2003) and Balliauw et al. (2019) who model uncertainty of expected growth and variability in demands using a stochastic process, we model efficiency of investment as uncertain. Second, we analyze the effects of information accumulation on investment timing, by incorporating a stochastic dominance approach into a discrete-time real options game setting. Third, we consider multiple uncertainties in the model framework, while further considering Knightian uncertainty (Knight, 1921) for the disaster occurrence probability. By introducing Knightian uncertainty into a real options game setting, we are able to provide a modelling framework that allows to account for both the (Knightian) uncertainty of climate change effects and uncertainty of investment efficiency.

The results suggest that information accumulation reduces the ports' investment size, while improving the discounted welfare associated with late investments. When competition is intensified, it is optimal for ports to invest in disaster prevention facilities earlier than later. However, immediate investments are less preferred when competition is weak, even lesser when the ports can acquire substantial information about the climate events and adaptation measures between the periods. Waiting is also a better option if the disaster occurrence probability is low or if the shippers' expected disaster losses are negligible. In other cases, the ports' investment decisions depend on the trade-off between the expected gain from competition, information accumulation, climate parameters such as the disaster occurrence probability, and the market conditions. These findings hold for both the public and private ports, though the former invest more than the latter do. The impacts of the model parameters on investment size are also more apparent for public ports. In most cases, social welfare is much higher with immediate investments, essentially because of the positive spillover effects on the surrounding areas and other sectors of economy.

The rest of the paper is organized as follows. Section 2 presents the model setup. We analyze the shippers' demands in Section 2.1, and investigate the terminal operator companies' problem in Section 2.2. Section 3 explores the ports' maximization problem. We first describe in details the adaptation costs for ports in Section 3.1, then solve the maximization problem for private ports in Section 3.2 and for public ports in Section 3.3. Section 4 displays the results. Section 5 discusses the implications for social welfare. In Section 6, we consider that the disaster occurrence probability is Knightian uncertain (instead of a fixed parameter) and discuss the implications for the modeling framework. Section 7 concludes.

2. The model

Consider a linear city with an infinite length served by two seaports (hereafter, we use term "port" for "seaport"), each consisting of a port authority (PA) and a downstream terminal operator company (TOC).[19] Port A is located at point 0 and port B at 1 (see Basso and Zhang, 2007). We assume that the decisions to invest in prevention facilities belong to the PAs.[20] Accordingly, the PAs choose the adaptation investments and quantities to be produced for each period so as to maximize discounted profits if they are private, and discounted local welfare if they are public. Then, they set the port fees to be charged to the downstream TOCs for land and facility use. The TOCs, in turn, compete with each other in quantities and

17 Nishimura and Ozaki (2007) also addressed investment decisions under Knightian uncertainty by investigating the effects of Knightian uncertainty on the value of irreversible investment opportunity. Recently, Niu et al. (2019) developed a model that introduces Knightian uncertainty into the standard model of capacity choice.

18 Balliauw et al. (2018) reviewed the relevant literature and risk factors in port capacity investment decisions under uncertainty. They also provided a survey of the studies that use real options in the transportation literature.

19 The terminal operator companies include transport companies, logistics operators, freight forwarders and liner shipping companies.

20 This assumption is consistent with some practices at the US ports. In some cases, the disaster resiliency and adaptation projects are part of the capital improvement of the port's budget. For example, the infrastructure disaster resiliency project at Port of Boston (2016–2020) is financed by Massport. The T-46 Lease stormwater system improvements project at Port of Seattle was included in the port's budget. In other cases, the funding comes from the federal government or from a combination of both sources (see for example, Port of Gulfport' restoration project funded by the US Department of Housing and Urban Development, Port of Miami' adaptation projects financed by the seaport funds and the federal department of transportation). Of course, there are exceptions where the TOCs and other stakeholders contribute to the decision on adaptation investments, but these cases are not considered in this analysis.

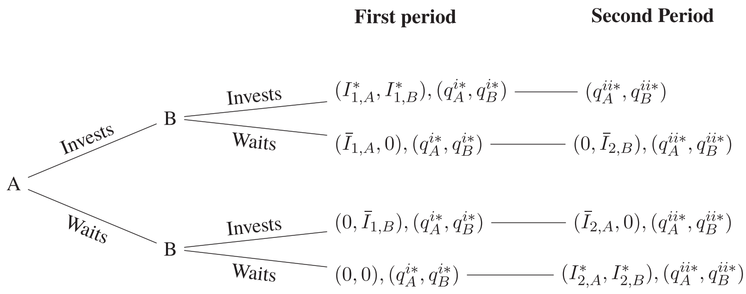

Fig. 1. Investment timing game and quantity competition in a two-period setting.

provide the shipping services (among others, loading and unloading) to the shippers (for example, exporters and importers). Fig. A.1 in Appendix A.1 gives a representation of the duopolistic competition between the two ports.

We consider two time periods, labeled *i* and *ii*, where *i* denotes first period and *ii* second period. At the beginning of the first period, the PAs decide whether they undertake adaptation investments immediately or wait until the next period. If the PAs invest immediately, the port facilities and shippers' assets are protected when a disaster happens during the first period, limiting the potential damage costs. If the PAs postpone the investments to the next period, they incur the maximum possible damage when a disaster occurs during the first period. Nevertheless, by waiting until the next period, the decision-makers can acquire better knowledge of both the adaptation projects and climate change-related disasters. Specifically, the motivation for ports to the postpone adaptation relies on the uncertainty of investment efficiency. Becker et al. (2013) provide insights into the sources of uncertainties around adaptation. First, scientific models predicting the climate change effects are still uncertain, while accurate identification of the potential risks and impacts is lacking. Second, identifying the stakeholders and creating new forms of collaboration among them remain a critical step at the early stage of adaptation. In particular, keeping the infrastructures operational goes beyond one group of stakeholders, but includes a wide set of public and private entities. Another consideration is that the ports have to identify the most appropriate and effective adaptation measures, by combining near-term and long-range planning that considers both hard and soft interventions (Ng et al., 2013).[21] Given the different sources of uncertainty around adaptation, we argue that the decision-makers can improve the efficiency of the investments by accumulating knowledge and information about the adaptation projects. In other words, information accumulation allows the decision-makers to reduce the uncertainties, thereby enhancing the investment efficiency.

Fig. 1 illustrates the real-options game in extensive form (tree) in line with Smit and Trigeorgis (2004). Consider the resulting terms at the end of each tree branch (port A, port B) in the following four investment-timing scenarios: (*i*) when both ports invest immediately (simultaneously), they choose equilibrium investments and then quantities $[(I^*_{1,A}, I^*_{1,B}), (q^{i*}_A, q^{i*}_B)]$ in the first period, and then set new quantities (q^{ii*}_A, q^{ii*}_B) in the second period; (*ii*)/(*iii*) when one port (A or B) invests first while the other waits (B or A), resulting in $[(\bar{I}_{1,A}, 0), (q^{i*}_A, q^{i*}_B)]$ in the first period and $[(0, \bar{I}_{2,B}), (q^{ii*}_A, q^{ii*}_B)]$ in the second period, or $[(0, \bar{I}_{1,B}), (q^{i*}_A, q^{i*}_B)]$ in the first period and $[(\bar{I}_{2,A}, 0), (q^{ii*}_A, q^{ii*}_B)]$; (*iv*) when both ports decide to wait and invest in the second period, they choose quantities (q^{i*}_A, q^{i*}_B) in the first period, then select investments and quantities $[(I^*_{2,A}, I^*_{2,B}), (q^{ii*}_A, q^{ii*}_B)]$ in the second period. Table A.1 in Appendix A.2 summarizes the decision-making of the competing ports during the first and second period, while Fig. A.2 describes the timing of the game in the form of tables.

We begin with the analysis of the shippers' demands.

2.1. Shippers' demands

Assume that the shippers are uniformly distributed along the infinite city with density one. Downstream TOCs (one at each port) offer services to shippers at price $\mathbf{p^T}$ and pay terminal fees, denoted by $\mathbf{f^T}$, to the PAs for facility use. The full price paid by the shippers at period *T* includes the service price charged by the TOC and transportation costs. The service price includes all charges of PAs, shipping lines and TOCs, inventory costs of cargo and the costs of delays borne by port users. We suppose that the shipper incurs an additional financial damage cost, denoted by $C^{S,T}_j$, which is associated with the potential natural disasters (for example, cessation or disruption of activities at the port during or after the disaster events). This cost, referred as "expected (or potential) disaster losses for shippers" can be reduced up to zero if the adaptation investments are made before the occurrence of the event. Reversely, the shippers will experience the maximum losses if no investments are undertaken beforehand. For analytical tractability, we specify the expected disaster losses for shippers as follows:

$$C^{S,T}_j = \gamma\, E\Big[Max\Big\{Dx - \theta_h I_j, 0\Big\}\Big], \quad \text{with} \quad j = \{A, B\}, \quad T = i, ii, \quad h = 1, 2, \tag{1}$$

[21] While hard interventions require high capital investments (human, material and financial), soft interventions involve reducing uncertainty in decision-making, notably systemic and strategic management planning instruments, such as land use management, financial incentives, evacuation schemes, and institutional changes.

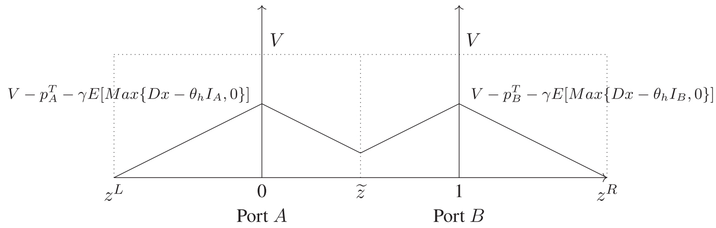

Fig. 2. Distribution of shippers along the linear city at period T.

where γ is a positive constant, superscript S denotes shippers, superscript T is the time period, D corresponds to the maximum financial damage incurred by the port without adaptation investments, x represents the disaster occurrence probability, assumed to be fixed, I_j denotes the adaptation investment made by port j, and θ_h captures the average efficiency of the investment. Subscript h on θ indicates the investment timing ("1" stands for the beginning of the first period and "2" for second period).

We suppose that θ_h is a random variable distributed over the positive support $[0, \theta_{\max}]$, with probability density function $g_h(\theta)$ and cumulative density function (CDF) $G_h(\theta)$. The true distribution of θ_h is unknown in both periods, though we assume that $g_h(\theta)$ is strictly positive. As stated in the introduction, the ports are assumed to gather more information about the potential disaster events and adaptation projects in the second period, i.e., some subset of the values of θ become known in the second period. This information gain is translated into a positive change in θ_h between the periods. Equivalently, the distribution of θ_2 (in the second period) is as large as the distribution of θ_1 (in the first period) in the sense of *First-degree Stochastic Dominance (FSD)*. Therefore, G_2 dominates G_1 by *FSD* for all $\theta \in [0, \theta_{\max}]$ and there are at least some θs for which a strong inequality holds.[22]

At each period T, a shipper derives net utility U_j^T when he/she transports cargo through port j, where:

$$U_A^T = V - p_A^T - C_A^{S,T} - tz; \quad U_B^T = V - p_B^T - C_B^{S,T} - t(1 - z),$$

where V denotes the gross benefit of the shipper, p_j is the shipping price (per unit of cargo) charged by the TOC at port j, t denotes road toll and z corresponds to the distance between the shipper's location and the chosen port. Fig. 2 gives a representation of the shippers along the city at period T.

To obtain the demand functions, we need to find the shipper that is indifferent between transporting cargo through either port. The indifferent shipper is located between the two ports, at $\tilde{z}$ in Fig. 2, and comes from equalizing U_A^T with U_B^T. It gives:

$$\tilde{z} = \frac{1}{2t}\left(t + p_B^T - p_A^T + C_B^{S,T} - C_A^{S,T}\right). \tag{2}$$

If we further assume that each port has its own captive market (a local monopoly), port A receives all shippers located in its left side and port B in its right side. The local market allows us to capture the size difference between the ports. Typically, large ports offer additional services (for example, improved ground accessibility to their facilities) so as to attract shippers and operators. Denote z^L and z^R the locations of the last shipper located on the left side of port A and on the right side of port B, respectively. The catchment areas of the ports are defined by z^L and z^R, where:

$$z^L = -\frac{V - p_A^T - C_A^{S,T}}{t}; \quad z^R = 1 + \frac{V - p_B^T - C_B^{S,T}}{t}. \tag{3}$$

Given the assumption of uniform distribution of shippers along the geographic location, we can define the port demands, denoted by $\mathbf{q^T} = (q_A^T, q_B^T)$, as $q_A^T = |z^L| + \tilde{z}$ and $q_B^T = z^R - \tilde{z}$. Thus, we obtain:

$$q_A^T = \frac{1}{2t}\left(t + 2V - 3C_A^{S,T} + C_B^{S,T} - 3p_A^T + p_B^T\right), \tag{4}$$

$$q_B^T = \frac{1}{2t}\left(t + 2V + C_A^{S,T} - 3C_B^{S,T} + p_A^T - 3p_B^T\right). \tag{5}$$

As expected, demands for shipping services at the ports are linear in prices, decrease in own prices but increase in that of the rival. They are, however, non-linear in road toll. For both facilities to receive positive demands, we set $(q_A^T, q_B^T) \geq 0$ and assume that V is large enough to exceed the full costs paid by the shippers, net of transportation cost.[23] We obtain the inverse demand functions for ports at each period by solving the system of equations in (4) and (5) for p_A^T and p_B^T, yielding:

$$p_A^T(\mathbf{q^T}) = \frac{1}{4}\left(2t + 4V - 4C_A^{S,T} - 3t\ q_A^T - t\ q_B^T\right), \tag{6}$$

[22] By definition, $g_h(\theta)$ satisfies the FSD property if the CDF of θ_2, $G_2(\theta)$, lies entirely or partly above the CDF of θ_1, $G_1(\theta)$, for all $\theta \in [0, \theta_{\max}]$, i.e. $G_2(\theta) \leq G_1(\theta)$ for all $\theta \in [0, \theta_{\max}]$ and there are at least some θs for which a strong inequality holds.

[23] Setting $(q_A^T, q_B^T) \geq 0$ implies $V \geq \frac{1}{2}(C_A^{S,T} + C_B^{S,T} + p_A^T + p_B^T - t)$, suggesting that V should be large enough to ensure positive demands at both ports.

$$p_B^T(\mathbf{q^T}) = \frac{1}{4}\left(2t + 4V - 4C_B^{S,T} - t\ q_A^T - 3t\ q_B^T\right), \tag{7}$$

where $\mathbf{q^T} = (q_A^T, q_B^T)$. Consumer surplus, denoted by CS_j^T, is the surface above the cost curve in Fig. 2, and is defined by distance $[z^L, \tilde{z}[$ for shippers using port A, and $]\tilde{z}, z^R]$ for shippers going to port B. The surplus of shippers transporting cargos through port j at period T is given by:

$$CS_j^T = \frac{t}{16}\left[7(q_j^T)^2 - (q_{-j}^T)^2 - 4q_j^T + 4q_{-j}^T + 2q_j^T q_{-j}^T - 4\right], \quad j = \{A, B\}, \quad T = i, ii. \tag{8}$$

Subscript $\{-j\}$ denotes the rival port. Total consumer surplus, denoted by CS^T, is the sum of the shippers' net benefits at both ports and is determined by:

$$CS^T = \frac{t}{8}\left[3(q_A^T)^2 + 3(q_B^T)^2 + 2q_A^T q_B^T - 4\right], \quad T = i, ii. \tag{9}$$

Having analyzed the shippers' demands, we examine the TOC's problem in the next section.

2.2. Terminal operator companies' problem

We consider two downstream TOCs (one at each port) that produce identical services to shippers. They compete with each other in quantities (in a Cournot fashion) so as to maximize profits. Each firm represents the shipping lines and other port service providers that contract with the TOCs. It pays port charge to the PA for land and facility use. The charge includes land lease and concession cost, i.e., the cost of port services such as towage, pilotage, mooring ship supply and port dues charged to shipping lines. Without loss of generality, the operational costs are assumed to be zero, and the operators have no fixed costs. We assume that the TOCs do not pay adaptation costs directly because of, among others, the short-to-medium term nature of their contracts. However, they are affected indirectly by the investment decisions of the PAs through the shippers' demands.[24]

The problem of TOC j at period T is:

$$\max_{q_j^T} \pi_j^T = p_j^T(\mathbf{q^T})\ q_j^T - f_j^T q_j^T, \quad j = A, B, \quad T = i, ii, \tag{10}$$

where $p_j^T(\mathbf{q})$ is given by Eqs. (6) and (7). Solving the first-order conditions with respect to $\mathbf{q^T}$ leads to the equilibrium quantities, denoted by $\mathbf{q^{*T}} = (q_A^{*T}, q_B^{*T})$, where:[25]

$$q_j^{*T} = \frac{2}{35t}\left[5(t + 2V) - 12C_j^{S,T} + 2C_{-j}^{S,T} - 12f_j^T + 2f_{-j}^T\right] \quad \text{where} \quad j = A, B, \tag{11}$$

where $C_j^{S,T} = \gamma\ E[Max\{Dx - \theta_h I_j, 0\}]$ with $h = 1, 2$ and $T = i, ii$. The quantity chosen by TOC j in equilibrium depends directly on port charges, road toll and the expected disaster losses for shippers.[26] In equilibrium, demand for shipping services decreases with the fee charged by the PA, but increases with the rival's fee. This reveals that the TOCs are substitutes. Interestingly enough, the competitive outputs of the TOCs are affected directly by the expected disaster losses for shippers. Specifically, higher expected losses reduce the shipping demand, inducing a loss of market share for the TOC. As we assume quantity competition between the TOCs, in equilibrium, the shipping prices adjust to clear the market. We obtain the expressions of the inverse demand functions for the TOCs by solving the system of equations in (11), with ,$j = A, B$ for f_A^T and f_B^T, leading to:

$$f_j^{*T}(\mathbf{q}^T) = \frac{1}{4}\left[2(t + 2V) - 4C_j^{S,T} - 6t\ q_j^T - t\ q_{-j}^T\right], \quad j = \{A, B\}, \quad T = i, ii. \tag{12}$$

It is easy to show that the profits of TOC j at period T, denoted by π_j^{*T}, are equal to $\frac{3t}{4}(q_j^{*T})^2$.[27] We now turn to the ports' problem.

[24] Of course, there are cases where the TOCs offer services to shippers at both competing ports, implying that if a disaster occurs and the port facilities are not resilient enough to handle the event, the TOC will reroute the shipment to the alternative port. This results in minimum losses for the shippers. To tackle this problem, one can consider a firm that acts like a monopoly at both ports, then chooses quantities so as to maximize the sum of the profits. The quantity set by the monopolist at port each port is $(q_{A,m}^T, q_{B,m}^T)$ where $q_{j,m}^T = \frac{1}{4t}(t + 2V - 3C_j^{S,T} + C_{-j}^{S,T} - 3f_j^T + f_{-j}^T)$ for $j = A, B$. This suggests that if a disaster occurs but both ports have invested in adaptation facilities early, the expected losses for shippers, $C_A^{S,T}$ and $C_B^{S,T}$ are reduced to zero, increasing the port demands. However, if one port, say port A, invests in adaptation and its rival waits until the next period, in the event of a disaster, the monopolist would still be able to reroute the traffic from port B to A so as to reduce the potential losses for shippers. As a result, the total demand for the monopolist would remain the same.

[25] The second-order derivatives with respect to quantities are negative $(\partial^2\pi_j | \partial q_j^{ii} = -3t|2 < 0$ for $j = A, B$ and the cross-derivatives are also negative $(\partial^2\pi_A | \partial q_A^T \partial q_B^T = \partial^2\pi_B | \partial q_B^T \partial q_A^T = -t|4 < 0)$, and $| -\frac{3t}{2}| > |\frac{t}{4}|$. So, the own effects dominate the cross effects, indicating that the maximum exists and is unique.

[26] To guarantee that both facilities receive positive demands, V must be large and satisfies $V \geq \frac{1}{2}(C_A^{S,T} + C_B^{S,T} + f_A^T + f_B^T - t)$.

[27] This expression is obtained by substituting q_j^T and f_j^T with q_j^{*T} and f_j^{*T} into the profit function in (10).

3. Ports' Problem

Following Wan and Zhang (2013), we consider two PAs that compete with each other in quantities at each period (see Fig. 2).[28] To capture the dynamic of the port resilience, we consider two periods of time (superscript i on variables stands for 'first period' and ii for 'second period'). The PAs choose adaptation investments $\mathbf{I} = (I_A, I_B)$ and outputs $\boldsymbol{q^T} = (q_A^T, q_B^T)$ so as to maximize the intertemporal objective function W_j, yielding:

$$\max_{\{\mathbf{I},\ \mathbf{q}^i,\ \mathbf{q}^{ii}\}} W_j = W_j^i + kW_j^{ii} = [\Pi_j^i + \alpha(\pi_j^i + CS_j^i)] + k[\Pi_j^{ii} + \alpha(\pi_j^{ii} + CS_j^{ii})] \quad \text{where}$$
$$\Pi_j^T = f_j^T q_j^T - C_j^T, \quad \pi_j^T = (p_j^T - f_j^T)\, q_j^T, \quad j = A, B, \quad T = i, ii, \tag{13}$$

where W_j^i and W_j^{ii} are the objective function of PA j during the first and second period, respectively, $0 < k \le 1$ designates the time discount factor ($k = e^{-r\delta}$ where r is the instantaneous rate of interest and δ is the real time between the periods), Π_j^T denotes profit of PA j at period T, π_j^T is TOC profit and CS_j^T is the consumer surplus obtained in (8). Parameter α captures the ports' ownership form, with $\alpha = 1$ for public ports and $\alpha = 0$ for private ones. In practice, there is a variety of ownership and management structures for ports, and the most common and conventional classification is the private/public ownership (Bichou and Gray, 2005). Therefore, the public ports maximize the local surplus if α is equal to one, while the objective function reduces to port profits when the α is equal to zero. Without loss of generality, we suppose zero operational costs for the PAs.

3.1. Adaptation costs for ports

Similarly to Xiao et al. (2015), we assume that the adaptation costs for ports depend on the investment timing. Specifically, the PAs choose to invest in adaptation facilities at the beginning of either the first or the second period. Accordingly, three configurations are considered: (i) both ports made "early" investments (i.e. in first period) and maintain the installed infrastructures in the next period, (ii) both ports wait and made "late" investments (i.e. in the second period), (iii) one port invests in the first period while its rival waits and postpones the investment to the second period. The respective costs of early and late investments for PA j at period T, are defined as follows:

$$C_{j,1}^i = I_j + E(Max\{Dx - \theta_1 I_j, 0\}), \qquad C_{j,1}^{ii} = k[\beta I_j + E(Max\{Dx - \theta_1 I_j, 0\})], \tag{14}$$

$$C_{j,2}^i = Dx, \qquad C_{j,2}^{ii} = k[I_j + E(Max\{Dx - \theta_2 I_j, 0\})], \quad \text{where} \quad j = A, B. \tag{15}$$

I_j denotes the financial cost of the investment, D is the maximum damage caused by a disaster, x is the disaster occurrence probability, with $0 \le x \le 1$. Parameter k corresponds to the time discount factor, with $0 \le k \le 1$ (k close to 0 indicates that the PA is impatient, whereas k close to 1 implies that it cares about the future welfare), and β represents the unit maintenance cost of the installed infrastructures, with $\beta < 1$. The restriction on β implies that maintaining the current infrastructures should be less costly than undertaking new investment. Otherwise, it is better to postpone the investment to the next period. Variable θ_h captures the efficiency of early ($h = 1$) and late ($h = 2$) investments.

The above equations suggest that if the investments are made earlier, PA j would bear the expected maximum possible damage costs during the first period, in addition to the initial financial cost. In the second period, the infrastructures are maintained at cost, βI_j, while the expected disaster-related damage costs remain the same. Clearly, the damage cost can be reduced to zero if the investments are made in a timely and efficient manner. Late investments lead the ports to incur the maximum damage, Dx, during the first period in the event of a disaster, while the financial cost of the investment, I_j, is paid at the beginning of the second period in conjunction with the expected possible damage costs.

For the remainder of the paper, we use the following notations:

$$\bar{\theta}_h^j(I_j) = \int_0^{Dx/I_j} \theta_h\, g_h(\theta)\, d\theta_h \quad \text{and} \quad G_h^j(I_j) = \int_0^{Dx/I_j} g_h(\theta)\, d\theta_h, \tag{16}$$

where $\bar{\theta}_h^j$ denotes the conditional mean of θ_h and G_h^j its associated CDF (superscript j on $\bar{\theta}_h$ and G_h refers to port j, as both terms depend on I_j). Note that when $\theta_h > Dx|I_j$, the expected damage from a potential disaster is zero. In such a case, the PAs have no incentives to invest in adaptation in the first place.[29] Hereafter, we shall focus on the case where $\theta_h \le Dx|I_j$. Table 1 summarizes the adaptation costs for ports.[30]

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[28] Some studies suggest that price competition captures better the ports' behaviour. Among others, see Basso and Zhang (2007) and De Borger et al. (2008). For comparison purpose, we conduct a similar analysis where the PAs compete in port charges and provide the results in Appendix A.10. We conclude that the nature of competition does not affect the main insights of the paper.

[29] It is also reasonable to assume that the ports invest more than the maximum possible damage. We leave this possibility of "over-investment" for future research.

[30] Details on the decomposition of the adaptation cost function are provided in Appendix A.4.

Table 1
Summary of the adaptation costs for port j over two periods.

Investment timing	$T = i$	$T = ii$
$h = 1$	$C_j^i = I_j + Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)$	$C_j^{ii} = k[\beta I_j + Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)]$
$h = 2$	$C_j^i = Dx$	$C_j^{ii} = k[I_j + Dx\ G_2^j(I_j) - I_j\bar{\theta}_2^j(I_j)]$

Note: These specifications are valid for $\theta_h \leq Dx|I_j$, where $j = A, B$ and $h = 1, 2$.

Having described the adaptation costs for ports, we now analyze the PAs' maximization problem. We investigate the cases where both ports undertake either early or late adaptation investments, and the case where one port invests early, while its rival postpones the investment to the next period. Private and public ports are analyzed separately. Note that the timing of the game depends on the investment decisions of the ports (for details, see Appendix A.2).

3.2. Case for private ports

3.2.1. Early investments by both private ports

When both PAs decide to invest in adaptation early, they choose their respective adaptation investments $\mathbf{I_1} = (I_{A,1}, I_{B,1})$ and quantities $\mathbf{q^i} = (q_A^i, q_B^i)$ in the first period, and then set new quantities $\mathbf{q^{ii}} = (q_A^{ii}, q_B^{ii})$ in the second period, while maintaining the installed infrastructures. The common way to solve the maximization problem is to proceed in a recursive manner. Specifically, we first need to find the optimal quantities in the last period given the investments and outputs chosen in the previous period, then solve the ports' maximization problem in the first period.

Usually, the PAs do not have complete information about the future strategies of competitors. In such case, they have to form expectations concerning rival's choice. For simplicity, we assume that port A supposes that port B maintains the same output during the two periods, i.e., $q_B^{ii} = q_B^i$, and port B reasons similarly about A (Friedman, 1968). In other words, we assume that the ports have *naive (or static) expectations*.[31] Under this assumption, port j aims at maximizing its discounted profits over the two periods, under the constraint $q_{-j}^{ii} = q_{-j}^i$. The maximization problem in (13) becomes:

$$\max_{\{\mathbf{I_1},\ \mathbf{q}^i,\ \mathbf{q}^{ii}\}} W_j \ = \ W_j^i + kW_j^{ii}, \quad s.t. \quad q_{-j}^{ii} = q_{-j}^i, \quad \text{with} \quad j = A, B, \tag{17}$$

where W_j is the discounted welfare defined in (13) in which α is replaced by 0. Without considering the constraint, the FOCs with respect to q_j^{ii} give:[32]

$$\frac{\partial W_j^{ii}}{\partial q_j^{ii}} \ = \ \frac{1}{4}\left(4V + 2t - 4\ C_j^{S,ii} - 12t\ q_j^{ii} - t\ q_{-j}^{ii}\right) = 0, \quad j = A, B. \tag{18}$$

Substituting the constraints into the above FOCs (18) leads to the new reaction functions given by:

$$q_A^{ii} = \frac{1}{12t}\left(tq_B^i + 4V + 2t - 4\ C_A^{S,ii}\right) = \Phi(q_B^i), \tag{19}$$

$$q_B^{ii} = \frac{1}{12t}\left(tq_A^i + 4V + 2t - 4\ C_B^{S,ii}\right) = \psi(q_A^i). \tag{20}$$

Equations $q_A^{ii} = \phi(q_B^i)$ and $q_B^{ii} = \psi(q_A^i)$ capture the dynamics of the adjustment process to the Nash-Equilibrium under the assumption of *naive expectations*. Note that q_B^{ii} and q_A^{ii} are replaced by, respectively, q_B^i and q_A^i in (19) and (20), and are supposed to be known by the players in the last period.[33] If we assume that $\mathbf{q^i}$ is the solution of the single-period Cournot game, i.e. $\mathbf{q^i} = \mathbf{q}^{*\mathbf{i}}$, the quantity produced by port j at period T in equilibrium is:[34]

$$q_j^{*T} \ = \ \frac{2}{143t}\left[11(2V + t) - 24C_j^{S,T} + 2C_{-j}^{S,T}\right], \quad \text{where} \quad j = A, B, \quad T = i, ii. \tag{21}$$

$C_j^{S,T}$ is the expected disaster losses for shippers transporting cargo through port j at period T defined in Eq. (1). By further decomposing the *Max* function in (1), the expected disaster loss function for shippers becomes:

$$C_j^{S,T} = \gamma\left[Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)\right], \quad \text{where} \quad \theta_1 \leq \frac{Dx}{I_j}. \tag{22}$$

[31] Using this assumption has an advantage in terms of analytical tractability. More importantly, it allows us to put more emphasis on the issue of size and timing of adaptation investment. Among the other alternatives, we have adaptive expectations and bounded rational expectations. For details, see Bresnahan (1981) for duopoly firms and Okuguchi (2013) for oligopoly.

[32] The second order conditions are satisfied as $\frac{\partial^2 W_j^{ii}}{\partial (q_j^{ii})^2} < 0$ with $j = A, B$.

[33] In other words, $\mathbf{q^i} = (q_A^i, q_B^i)$ is exogenous to ports in the second period.

[34] The second order conditions are satisfied since $\frac{\partial^2 W_j^{ii}}{\partial (q_j^{ii})^2} = t(-3 + 19\alpha/8) < 0$ for $\alpha = 0, 1$. Moreover, we can easily show that a sufficient condition for the asymptotic stability of the Nash-Equilibrium, i.e. $(q_A^{ii}, q_B^{ii}) \to (q_A^{*ii}, q_B^{*ii})$, is: $|\frac{d\phi}{dq_B^{ii}}||\frac{d\psi}{dq_A^{ii}}| < 1$ is fulfilled in our setup.

As shown by Eq. (21), the difference between the quantities set by the ports in the first and second period is captured by terms $C_j^{S,T}$ and $C_{-j}^{S,T}$. Hence, the dynamic nature of the port's problem is transferred through the investment costs and the associated expected disaster losses borne by the shippers. For given adaptation investments, the (equilibrium) quantities at each period increase with the gross benefit of shippers but decrease with road toll. Essentially, an increase in road toll rises the full cost borne by the shippers, inducing a decrease in shippers' demands. Moreover, large disaster damage and high disaster occurrence probability reduce the port demands. This is explained by the fact that, other things being equal, shippers would use the most resilient port as they want to minimize the costs and expected losses associated with potential disasters.

The next step consists of determining the optimal adaptation investments made by ports. By first ignoring the constraint $\theta_1 I_j \leq Dx$, the FOCs with respect to adaptation investment $\mathbf{I_1}$ yields:[35]

$$\frac{\partial W_j}{\partial I_j} = \bar{\theta}_1^j(I_j)\left[\frac{144}{143}\gamma\,(q_j^{*i} + kq_j^{*ii}) + (1+k)\right] - (1+k\beta) = 0,$$

where $j = \{A, B\}$, $\bar{\theta}_1^j$ is the conditional mean of investment efficiency θ_1 defined in (16), q_j^{*i} is the (equilibrium) quantity obtained in (21) with $T = i$. Note that port demands, $\mathbf{q^{*i}}$ and $\mathbf{q^{*ii}}$ depend on the conditional mean and CDF of θ_1, which in turn are affected by the levels of adaptation investments. Before solving the FOCs, we first define the following notations:

$$f_h(\theta) = \theta_h\; g_h(\theta) \quad \text{and} \quad F_h(a) = \int_0^a \theta_h\; f_h(\theta) \quad \text{where} \quad h = \{1, 2\}. \tag{23}$$

The optimal adaptation investments for private ports, denoted by $\mathbf{I}_1^* = (I_{A,1}^*, I_{B,1}^*)$, are the solutions of the following FOCs:

$$I_{j,1}^* = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m_j^0(\mathbf{I_1^*})}\right]}, \quad \text{where} \quad m_j^0(\mathbf{I_1^*}) = \frac{144}{143}\gamma\left(q_j^{*i} + kq_j^{*ii}\right) + (1+k), \quad j = A, B.$$

To guarantee an interior solution, constraint $I_{j,1}^* \leq Dx|\theta_1$ must be satisfied, implying $\theta_1 \leq F_1^{-1}\left[\frac{1+k\beta}{m_j^0(\mathbf{I_1^*})}\right]$ for all $\theta \in [0, \theta_{\max}]$. The discounted profits of port j in equilibrium become:

$$\Pi_{j,1}^* = f_j^{*i}\; q_j^{*i} + k\; f_j^{*ii}\; q_j^{*ii} - (1+k\beta)\; I_{j,1}^* - (1+k)\left[G_1^j(I_{j,1}^*) - I_{j,1}^*\; \bar{\theta}_1^j(I_{j,1}^*)\right], \quad j = A, B.$$

3.2.2. Late investments by both private ports

In this section, we analyze the case where both PAs wait until the next period to invest in adaptation facilities. The motivation for ports to postpone the investment is to accumulate information, which allows one for reducing the uncertainty of investment efficiency. Regarding the timing of the game, the PAs simultaneously choose quantities in the first period, then decide on the optimal adaptation investments and new outputs in the second period. Like the previous analysis, the decision-making process is solved backwards.

Maximizing the discounted profits in (17) leads to the same expressions as in (21), except for the disaster expected losses for shippers. Then, we have:

$$q_j^{*ii} = \frac{2}{143t}\left[11(2V+t) - 24C_j^{S,ii} + 2C_{-j}^{S,ii}\right], \quad \text{where} \tag{24}$$

$$C_j^{S,ii} = \gamma\left[Dx\; G_2^j(I_j) - I_j\; \bar{\theta}_2^j(I_j)\right] \quad \text{if} \quad \theta_2 \leq \frac{Dx}{I_j}, \quad j = A, B, \tag{25}$$

where $\bar{\theta}_2^j(I_j)$ is the conditional mean of the late investment efficiency defined in (16) and $G_2(\theta)$ its associated CDF.

The next step consists of determining the levels of investment chosen by the PAs. Since the investment decisions are made at the beginning of the second period, the port profits and the shippers' potential disaster losses in the first period do not depend on term $\mathbf{I_2}$. In other words, if a disaster occurs in the first period, the ports incur maximum possible damage Dx and the corresponding losses for shippers are captured by term γDx. Hence, the maximization problem of port j, given $\mathbf{q^i}$, can be rewritten as follows:

$$\max_{I_j}\; W_j(\mathbf{I_2}) = W_j^i + kW_j^{ii}\;(\mathbf{I_2}) \quad s.t. \quad \theta_2 I_j \leq Dx, \quad \text{for} \quad j = A, B,$$

where $\mathbf{I_2} = (I_{A,2}, I_{B,2})$. The first order conditions with respect to $\mathbf{I_2}$ yield:[36]

$$\frac{\partial W_j}{\partial I_j} = k\; \bar{\theta}_2^j(I_j)\left(\frac{144}{143}\gamma q_j^{*ii} + 1\right) - k = 0, \quad j = A, B, \tag{26}$$

[35] The second order conditions are satisfied, i.e., $\frac{\partial \Pi_j^2}{\partial I_j^2} \leq 0$ for $\theta_1, g_1, q_j^{*T}, f_j^{*T} \geq 0$ with $j = A, B$ and $T = i, ii$.

[36] The second order conditions are satisfied, as $\frac{\partial \Pi_j^2}{\partial I_j^2} < 0$ when $q_j^{*ii}, g_2(\theta) > 0$ for $j = A, B$.

where $\bar{\theta}_2^j(I_j)$ is given by (16) with $h=2$. Again, quantity q_j^{*ii} and cost $C_j^{S,ii}$ in (26) depend on the port adaptation. Using the same notation as in (23) with $h=2$, we characterize the optimal levels of investments $\mathbf{I_2^*} = (I_{A,2}^*, I_{B,2}^*)$ through the following equations:

$$I_{j,2}^* = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}_j^0(\mathbf{I_2^*})}\right]} \quad \text{where} \quad \bar{m}_j^0(\mathbf{I_2^*}) = \frac{144}{143}\gamma q_j^{*ii} + 1. \tag{27}$$

The condition to be guaranteed for an interior solution at equilibrium, $I_{j,2}^* \le Dx|\theta_2$, becomes $\theta_2 \le F_2^{-1}[1|\bar{m}_j^0(\mathbf{I_2^*})]$ for all $\theta \in [0, \theta_{\max}]$ where $j=A,B$. If we assume that the strategies of the private ports during the first period are the solutions of the single-Cournot game, the equilibrium quantities in period i are similar to (21), with $T=i$ and $C_j^{S,i}$ replaced by γDx. That is:

$$q_j^{*i} = \frac{2}{143t}\left[11(2V+t) - 24C_j^{S,i} + 2C_{-j}^{S,i}\right], \quad \text{where} \quad C_j^{S,i} = \gamma Dx, \quad j=A,B. \tag{28}$$

The discounted profits for the private PAs undertaking late investments are obtained by substituting the adaptation investment in (13) with the solution of (27), the adaptation costs with the expressions provided in line 2 ($h=2$) of Table 1, quantities with (28) and (24) and α with zero. We obtain:

$$\Pi_{j,2}^* = (f_j^{*i}\ q_j^{*i} - Dx) + k\ \{f_j^{*ii}\ q_j^{*ii} - [I_{j,2}^* + Dx\ G_2^j(I_{j,2}^*) - I_{j,2}^*\ \bar{\theta}_2^j(I_{j,2}^*)]\}, \text{ where } j=A,B.$$

3.2.3. Alternate investments by private ports

Assume that port A (or port B) invests in adaptation in the first period, but its rival waits until the next period to undertake investments. In such a case, the adaptation investments are not chosen simultaneously, but separately. It is equivalent to assume that adaptation investments are exogenous. Therefore, the efficiency of investment made by port A is θ_1, while that of port B is θ_2. The (equilibrium) quantities chosen by the PAs at each period remain the same, i.e.,

$$q_A^{*T} = \frac{2}{143t}\left[11(2V+t) - 24C_A^{S,T} + 2C_B^{S,T}\right], \quad q_B^{*T} = \frac{2}{143t}\left[11(2V+t) - 24C_B^{S,T} + 2C_A^{S,T}\right],$$

where $T=\{i, ii\}$ and for all $\theta_h \le Dx/I_j$ with $h=1,2$. However, the expected disaster losses for shippers differ. Specifically, we have:

$$C_A^{S,T} = \gamma\left[Dx\ G_1^A(I_A) - I_A\ \bar{\theta}_1^A(I_A)\right], \quad C_B^{S,i} = \gamma Dx, \quad C_B^{S,ii} = \gamma\left[Dx\ G_2^B(I_B) - I_B\ \bar{\theta}_2^B(I_B)\right],$$

where $T=i, ii$. Since the investment timing of the ports differs, the expected losses for shippers are no longer symmetrical. From the shippers' point of view, using port A would be a better choice in the first period because the port facilities are more resilient. The corresponding discounted profits for each PA are:

$$\Pi_{A,1}^* = f_A^{*i}\ q_A^{*i} - [I_{A,1}^* + Dx\ G_1^A(I_{A,1}^*) - I_{A,1}^*\ \bar{\theta}_1^A(I_{A,1}^*)] + k\ \{f_A^{*ii}\ q_A^{*ii} - [\beta I_{A,1}^* + Dx\ G_1^A(I_{A,1}^*) - I_{A,1}^*\ \bar{\theta}_1^A(I_{A,1}^*)]\}$$

$$\Pi_{B,2}^* = f_B^{*i}\ q_B^{*i} - Dx + k\ \{f_B^{*ii}\ q_j^{*ii} - [I_{B,2}^* + Dx\ G_2^B(I_{B,2}^*) - I_{B,2}^*\ \bar{\theta}_2^B(I_{B,2}^*)]\}, \quad \text{where} \quad j=A,B.$$

The conditions to be guaranteed for interior solutions obtained in the previous analyses also apply for the cases where the PAs invest at different times.

3.3. Case for public ports

In this section, we consider two public PAs that compete with each other in quantities so as to maximize discounted welfare. The maximization problem is similar to (13), but α is replaced by 1.

3.3.1. Early investments by both public port authorities

The procedures to solve the ports' maximization problem are the same as in the analysis for the private ports. To save space, we abstract away the details, while focusing on the results. The solutions of the FOCs with respect to $\mathbf{q_j^T}$, after considering constraints $q_{-j}^{ii} = q_{-j}^{i}$, are:[37]

$$q_j^{*T} = \frac{1}{3t}\left(4V + t - 5C_j^{S,T} + C_{-j}^{S,T}\right), \quad \text{where} \quad C_j^{S,T} = \gamma[Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)], \tag{29}$$

where $j=A,B$ and $T=i, ii$. By comparing the equilibrium demands of the private (21) and public (29) ports under the assumptions of identical adaptation investments across ports, we find that public ports receive higher demands than the private ones. This can be explained by the higher terminal fees charged by the profit-maximizing private ports, which increase the full costs paid by the shippers. The FOCs with respect to adaptation investments $\mathbf{I_1}$ yield:

$$\frac{\partial W_j}{\partial I_j} = \bar{\theta}_1^j(I_j)\left\{\frac{\gamma}{6t}[6t(q_j^{*i} + kq_j^{*ii}) - t(q_{-j}^{*i} + kq_{-j}^{*ii}) + 2V(1+k) - (C_{-j}^{S,i} + kC_{-j}^{S,ii})] + (1+k)\right\} - (1+k\beta) = 0,$$

[37] The second order conditions are satisfied.

where $j = \{A, B\}$ and subscript $\{-j\}$ denotes the rival port. Using the same notations as in (23), the optimal size of adaptation investments for the public PAs are characterized by the following equations:

$$I^*_{j,1} = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m^1_j(\mathbf{I^*_1})}\right]}, \quad j = A, B, \quad \text{where} \tag{30}$$

$$m^1_j(\mathbf{I^*_1}) = \frac{\gamma}{6t}\left[6t(q^{*i}_j + kq^{*ii}_j) - t(q^{*i}_{-j} + kq^{*ii}_{-j}) + 2V(1+k) - (C^{S,i}_{-j} + kC^{S,ii}_{-j})\right] + (1+k). \tag{31}$$

The condition for an interior solution becomes $\theta_1 \leq F_1^{-1}[(1+k\beta)|m^1_j(\mathbf{I^*_1})]$ for all $\theta \in [0, \theta_{\max}]$. In equilibrium, the discounted welfare of PA j is determined by:

$$W^*_{j,1} = (CS^{*i}_{j,1} + kCS^{*ii}_{j,1}) + (\pi^{*i}_{j,1} + k\pi^{*ii}_{j,1}) + \{f^{*i}_j\ q^{*i}_j + k\ f^{*ii}_j\ q^{*ii}_j - (1+k\beta)\ I^*_{j,1} - (1+k)\ [G^j_1(I^*_{j,1}) - I^*_{j,1}\ \bar{\theta}^j_1(I^*_{j,1})]\},$$

where f^{*T}_j and q^{*T}_j are the (equilibrium) port fee and quantity set by public PA j at period T, respectively, $I^*_{j,1}$ is the solution of Eq. (30), $\pi^{*T}_{j,1}$ is the (equilibrium) profit of the downstream TOC and $CS^{*T}_{j,1}$ is the consumer surplus at period T.

3.3.2. Late investments by both public port authorities

Now, consider that the PAs wait until the next period to undertake adaptation investments. We proceed in the same way as in Section 3.2.2, except that parameter α is equal to 1 and $h = 2$. The quantity set by public PA j in the second period in equilibrium, for all $\theta_2 \leq \frac{Dx}{I_j}$, becomes:

$$q^{*ii}_j = \frac{1}{3t}\left(4V + t - 5C^{S,ii}_j + C^{S,ii}_{-j}\right), \text{ where } C^{S,ii}_j = \gamma\left[Dx\ G_2(I_j) - I_j\ \bar{\theta}^j_2(I_j)\right], \tag{32}$$

where $j = A, B$. Similarly, $\bar{\theta}^j_2$ denotes the conditional mean of the "late" investment efficiency, defined in (16). The adaptation investments chosen by the public PAs, denoted by $\mathbf{I_2} = (I_{A,2}, I_{B,2})$, are the solutions of the following maximization problem:

$$\max_{I_{j,2}} W_j(\mathbf{I_2}) = W^i_j + kW^{ii}_j\ (\mathbf{I_2}) \quad s.t. \quad \theta_2 I_j \leq Dx, \quad \text{for} \quad j = A, B.$$

The first order conditions with respect to $\mathbf{I_2}$ yield:[38]

$$\frac{\partial W_j}{\partial I_j} = k\bar{\theta}^j_2(I_j)\left[\frac{\gamma}{6t}\left(6tq^{*ii}_j - tq^{*ii}_{-j} + 2V - C^{S,ii}_{-j}\right) + 1\right] - k = 0, \quad j = A, B,$$

Using the same notation as in (23) with $h = 2$, we characterize the optimal levels of the adaptation investments by public PAs, $\mathbf{I^*_2} = (I^*_{A,2}, I^*_{B,2})$, through the following equations:

$$I^*_{j,2} = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}^1_j(\mathbf{I^*_2})}\right]} \quad \text{where} \quad \bar{m}^1_j(\mathbf{I^*_2}) = \frac{\gamma}{6t}\left(6tq^{*ii}_j - tq^{*ii}_{-j} + 2V - C^{S,ii}_{-j}\right) + 1. \tag{33}$$

The condition to be guaranteed for an interior solution at equilibrium, $I^*_{j,2} \leq Dx|\theta_2$, becomes $\theta_2 \leq F_2^{-1}[1|\bar{m}^1_j(\mathbf{I^*_2})]$ for all $\theta \in [0, \theta_{\max}]$ and $j = A, B$. If the strategies of the public PAs during the first period are the solutions of the single-Cournot game, the quantities set in first period are similar to (29), where $T = 1$ and $C^{S,i}_j = \gamma Dx$. That is:

$$q^{*i}_j = \frac{1}{3t}\left(4V + t - 5C^{S,i}_j + C^{S,i}_{-j}\right), \quad \text{where} \quad C^{S,i}_j = \gamma Dx, \quad j = A, B. \tag{34}$$

Eq. (34) suggests that the shippers using the public ports will bear the maximum possible damage if a disaster occurs in the first period because no prevention investments are undertaken by the public authorities. The discounted welfare of the public PAs in equilibrium read:

$$W^*_{j,2} = \left(CS^{*i}_{j,2} + k\ CS^{*ii}_{j,2}\right) + \left(\pi^{*i}_{j,2} + k\ \pi^{*ii}_{j,2}\right) + \left[f^{*i}_j\ q^{*i}_j - Dx + k\ f^{*ii}_j\ q^{*ii}_j - k(I^*_{j,2} + Dx\ G^j_2(I^*_{j,2}) - I^*_j\ \bar{\theta}^j_2(I^*_{j,2}))\right],$$

where f^{*T}_j and q^{*T}_j are the (equilibrium) port fee and quantity set by public PA j at period T, respectively, $I^*_{j,2}$ is the solution of Eq. (33), $\pi^{*T}_{j,2}$ and $CS^{*T}_{j,2}$ are the corresponding TOC profits and consumer surplus.

[38] The second order conditions are satisfied, as $\frac{\partial \Pi^2_j}{\partial I^2_j} < 0$ when $q^{*ii}_j, g_2(\theta) > 0$ for $j = A, B$.

Table 2
Parameter values for simulation.

Parameter	Value	Definition
V	1	Gross benefit of shippers
k	0.5	Discount rate
x	0.1	Disaster occurrence probability
β	$0.01 * I_j^*$	Maintenance cost
D	1	Maximum possible damage (% of GDP)
t	0.05	Road toll
γ	0.1	Proportion of expected disaster losses incurred by shippers

Note: Details on the parameter choice and related sources are provided in Appendix A.3.

3.3.3. Alternate investments by public port authorities

This section follows directly from the above analysis. If one public PA invests in the first period while its rival waits until the second period, the investments are not chosen simultaneously, thus considered as exogenous. For the case where we assume that public port A invests in the first period and port B in second period, we obtain equilibrium quantities similar to (29) for port A where period $T = \{i, ii\}$, whilst the outputs chosen by port B is given by (34) and (32). The welfare functions of the public PAs are:

$$W_{A,1}^* = (CS_{A,1}^{*i} + k\ CS_{A,1}^{*ii}) + (\pi_{A,1}^{*i} + k\ \pi_{A,1}^{*ii}) + \{f_A^{*i}\ q_A^{*i} + k\ f_A^{*ii}\ q_A^{*ii} - (1+k\beta)\ I_{A,1}^* - (1+k)\ [G_1^A(I_{A,1}^*) - I_{A,1}^*\ \bar{\theta}_1^A(I_{A,1}^*)]\},$$
$$W_{B,2}^* = \left(CS_{B,2}^{*i} + k\ CS_{B,2}^{*ii}\right) + \left(\pi_{B,2}^{*i} + k\ \pi_{B,2}^{*ii}\right) + \left\{f_B^{*i}\ q_B^{*i} - Dx + k\ f_B^{*ii}\ q_B^{*ii} - k[I_{B,2}^* - Dx\ G_2^B(I_{B,2}^*) - I_{B,2}^*\ \bar{\theta}_2^B(I_{B,2}^*)]\right\}.$$

Note that the potential losses for shippers are also affected by the investment and timing decisions of the port authorities.

The analytical results for the private and public ports are summarized in Table A.2 in Appendix A. The next section compares each case and discusses the main findings.

4. Results

The analytical results emphasize that the investment size depends on functions $F_1^{-1}(.)$ and $F_2^{-1}(.)$, which in turn rely on the distribution of investment efficiency during the first and second period.[39] To proceed, we assign specific distributions to the investment efficiencies, θ_1 and θ_2, and conduct numerical simulations using reasonable values of parameters.[40]

We assume that the investment efficiency follows lognormal distribution. We argue that lognormal is a reasonable distribution for investment efficiency, as its density function is defined only on the positive range. Moreover, it is commonly known that the distributions of rates of return to investment are positively skewed. Consider $\theta_1 \sim \Lambda(\mu_1, \sigma_1)$ and $\theta_2 \sim \Lambda(\mu_2, \sigma_2)$, where Λ stands for lognormal distribution, μ_h and σ_h are the means and standard deviations of $log(\theta_h)$, respectively. Denoting G_1 and G_2 the respective CDF of θ_1 and θ_2, we say, G_2 dominates G_1 by First Stochastic Dominance (FSD) if and only if $\mu_2 > \mu_1$ and $\sigma_1 = \sigma_2$ (Levy, 2015). Since the analytical tractability of the model remains challenging, even after replacing $F_1^{-1}(.)$ and $F_2^{-1}(.)$ with their functional forms, we proceed with numerical simulations to get the main insights from the model. Table 2 lists the parameter values used in the simulation exercise.

For testing purposes, we choose arbitrary values for μ_h and σ_h. Therefore, we set $\mu_1 = 0.2$, $\mu_2 = 1.2$ and $\sigma_1 = \sigma_2 = 0.1$.[41] Hence, without information accumulation, we have $\mu_1 = \mu_2 = 0.2$. Figs. A.5–A.7 in Appendix A.5 present the simulation results when investments are chosen simultaneously by the private ports and Figs. A.8–A.10 in Appendix A.6 show the findings for the public ports under the same scenarios.[42]

4.1. Results for private ports

In this section, we discuss the results of the simulation exercise for the private ports. We analyze the best option for the ports in terms of investment timing, when the parameter of interest changes. Since we are also interested in the impact of information accumulation, we present the findings without information accumulation in the left panels of each figure in Section A.5 of Appendix A and the ones with information accumulation in the right panels.

[39] Comparing two general distributions, solving the associated maximization problem, and substituting the solutions into the adaptation costs and discounted profit functions, if feasible, are tedious and very difficult. We leave this possibility for future research.

[40] Details on the parameter choice are provided in Section A.3 in Appendix A.

[41] These values do not reflect real-world cases but are chosen for testing purposes only. We conduct sensitivity analyses with different values of μ_h and σ_h and obtain similar insights from the model.

[42] For the sake of clarity, we do not report the simulation results when investments are made at different times. However, these results are available upon request.

4.1.1. Impacts of competition and information accumulation

We begin by analyzing the optimal timing of adaptation investments for private ports, when the level of competition changes. In our setup, competition between ports is captured by road toll t, with low (large) road toll indicating strong (weak) rivalry. To capture the competition effects, we consider two levels of road toll: (i) low ($t_l = 0.01$) and (ii) high ($t_h = 0.7$).

In general, the ports' discounted profits decrease when road toll increases. High road toll increases the full costs paid by the shippers, which in turn induces a reduction in demands for cargo shipment through the ports. Reversely, low road toll stimulates the port demands, as the shippers pay less in transportation costs. When competition is intensified but there is no potential information gain between the periods, it is better for ports to invest earlier than later. However, early adaptation is less preferred when rivalry between ports is weak (high road toll). The difference between the discounted profits becomes even smaller when there is a possibility to accumulate information about the adaptation projects and potential climate events. More specifically, information gain improves the efficiency of late adaptation investment, resulting in reduction in its size, while improving the discounted profits (Π_2). This is demonstrated by the shift to the left of the profit functions (Π_2) in the top two right panels in Fig. A.5.

We identify two mechanisms by which late adaptation in conjunction with information accumulation may reduce the size of investment. First, early investments improve the resilience of the port infrastructures early on, boosting the confidence of the shippers put upon the ports, as the risk of loosing their assets in the event of disasters is low. Consequently, demands over the two periods increase. As the number of shippers increases, larger investments are required. Moreover, the existing customers need to be served effectively (PEER, 2006). Reversely, with late investments, the ports receive lower demands over the two periods, lowering the investment size. The second mechanism is the improvement in investment efficiency. It is well-known that better efficiency implies lower costs to produce the same output. With information accumulation, the PAs would be able identify the best adaptation strategies and stakeholders over time. Therefore, the total adaptation costs will be reduced.

When the adaptation investments are made at different times, as discussed in Section 3.2.3, the size of adaptation is decided separately, therefore considered as exogenous. In our simulation exercise, we assume that port A chooses investment that maximizes its own discounted profits and port B behaves similarly. The simulation results show that early adaptation is a better option for private ports when the investment decisions are made individually at different times. The PA undertaking late investment would experience a reduction in demands during the first period, leading to profit loss because of the lack of protection and disaster-resilient port infrastructures.[43] It appears that the benefit from information accumulation cannot compensate the reduction in revenue, especially when the rival port undertakes early adaptation. This result implies that adaptation investment can be used by ports as a strategic variable for competing with the rival.

4.1.2. Impacts of disaster occurrence probability, maximum possible damage and information accumulation

To investigate the impact of occurrence disaster probability, we consider two scenarios, including low ($x = 0.1\%$) and high occurrence probability ($x = 20\%$). The simulation results show that the broader the disaster occurrence probability, the larger the adaptation investments are. While the size of early and late investments is almost identical when the occurrence probability is very low, regardless of the level of information accumulation, the size difference becomes more apparent when the disaster probability gets higher. It even becomes larger in the presence of information accumulation. As discussed in Section 4.1.1, the ports would receive higher demands if they invest in adaptation earlier rather than later, especially if the risk of being hit by natural disasters is (very) high. Clearly, if the ports' assets are highly exposed to potential disasters, the ports need to invest in adaptation as soon as possible to protect their facilities. In this case, early investments result in a significant cost reduction by lowering disaster losses for shippers and the expected damage costs for the TOCs and ports. Even if postponing the investment decisions until the next period allows the ports to reduce the size of adaptation while increasing the discounted profits, the PAs are still better off undertaking early adaptation when the disaster probability is high. Waiting is a better option, only if there's a low chance of disaster occurrence.[44] This reasoning also applies when investments are made separately at different times. This has been typically the case of ports located in high elevation areas (for e.g., Port of Los Angeles, Port of Savannah).[45] This finding is also consistent with the existing literature (Xiao et al., 2015). The effects of maximum possible damage (D) on the size of adaptation investments and on ports' discounted profits are expected to be similar to that of the disaster occurrence probability (x), as both parameters enter in the same way into the investment and profit functions in equilibrium (see Table A.2).

[43] This has been the case of Gulfport when it experienced total devastation after Hurricane Katrina. Containers from the terminals washed up throughout the downtown area, while piers and warehouses were destroyed. Moreover, the customers lost their cargos stored at the ports and most of them were relocated (Becker et al., 2012). The exceptions include TOCs operating at both competing ports, which can redirect the shippers to the most resilient port when a disaster occurs.

[44] In practice, the most advanced ports in terms of implementation of adaptation strategies and improvement of the resilience of the infrastructures are those at higher risk (e.g., Port of New York and New Jersey, Port of New Orleans, Port of Gulfport, Port of Tokyo).

[45] Port of Los Angeles (PoLA) is at low risk impacts from sea level rise through 2050 since PoLA's terminals are relatively high above today's mean sea level and have never been flooded in the past few decades. As a result, PoLA decided that it will only consider sea level rise during a major upgrade of terminals planned for the future (Lempert et al., 2012). Port of Savannah's response to the minor level of risk posed by climate change effects is similar. Although the structure's effectiveness could be reduced slightly with the projected sea-level rise rates, the port decided to address the issue through immediate adaptive management of the mitigation features and through future adaptation plans.

4.1.3. Impacts of discount factor, maintenance cost, expected disaster loss for shippers and information accumulation

We run simulations with two different levels of k, namely low ($k_l = 0.01$) and high ($k_h = 0.7$) factor. The low discount factor indicates that the ports attribute lower value to the future profits, while the large one suggests higher value. In general, an increase in discount factor improves the ports' discounted profits. Similarly to the previous cases, information accumulation decreases the level of adaptation required in the second period (I_2^*). Without information accumulation, the difference in discounted profits is not significantly large with low discount factor. However, immediate investments lead to better outcomes when the discount factor is large. The profit difference gets tighter again when the ports can acquire more information between the periods. It is certainly reasonable to postpone the adaptation projects when the cost of waiting for more favourable opportunities is very low. However, when waiting starts to become costly, undertaking immediate investments represents a better option. When investments are made at different times, the port that invests early always appears to get higher discounted profits, regardless the level of discount factor. While information accumulation decreases the adaptation size of the one that invests in the second period, while increasing its discounted profits. The benefit from information gain still cannot make up for the loss of profits due to the decrease in demand during the first period.

Regarding the impact of maintenance cost (β), we also try two different levels of cost, including low ($\beta_l = 0.01{*}I_j$) and high ($\beta_h = 0.7{*}I_j$). Surprisingly, the maintenance cost appears to have little influence on the optimal size of investment and timing decisions of the ports when there is no information accumulation. Undertaking early investments always appears to be optimal for the ports under these scenarios. However, information gain over the periods leads to a decrease in the adaptation size, improving of the associated discounted profits. As a result, early investments become less preferred. As Xiao et al. (2015) argued, the ports are better off making new adaptation investments in the next period when the maintenance cost is large. In addition to that, the ports can improve the investment efficiency by acquiring additional information on the adaptation projects. The main findings remain valid when the investments are assumed to be made at different times.

To capture the effects of expected disaster losses for shippers and information accumulation, we look into the change in ports' discounted profits when parameter γ varies. We set two different (arbitrary) values of γ: low ($\gamma_l = 0.1$) and high ($\gamma_h = 0.7$). When parameter γ is low, suggesting that the shippers' demands are less affected by the investment decisions of the ports, it is clear that there is a potential benefit for ports to postpone the adaptation to the next period. If waiting involves information accumulation, the ports can even be better off with late investments. However, when the shippers are more sensitive to the investment decisions of the ports (high γ), it is optimal for ports to invest as early as possible. Indeed, if a disaster occurs and the facilities are not protected enough, the expected losses for the shippers would be substantial, especially if there is no plan to reroute to other ports. Demands will drop, so as the discounted profits. In this case, even with information accumulation, undertaking early investments remains a better option because the reduction in demands is too large to be compensated by the potential information gain. The same reasoning applies when investments are made separately and at different times by the ports.

4.2. Results for public ports

In this section, we explore the impacts of model parameters and information accumulation on adaptation size and discounted welfare for public port authorities. The same parameter values presented in Table 2 and described in Section A.3 and are used to derive the main results for the public ports. We also consider the same scenarios, including low and high values of parameters, to allow for comparability of results across private and public ports.

Not surprisingly, we obtain similar effects as the private ports regarding the impacts of information accumulation. Specifically, information accumulation decreases the adaptation size made by the public PAs in the second period, while increasing the total discounted welfare. On one hand, we have shown in Section 4.1 that information gain improves the discounted profits of the ports. One the other hand, the public PAs also take into consideration the advantages of shippers and TOCs arising from information accumulation.

Regarding the impacts of road toll, we obtain similar patterns as the private ports. Public ports tend to invest earlier than later, regardless of the level of competition. Early investments not only lead to increased port demands and profits but also improve the consumer surplus along with the TOC profits. When comparing the public PAs with the private ones, the former appear to always invest more in adaptation size. Moreover, the impact of investment decisions on discounted welfare is more apparent for the public ports. This is not surprising as the public ports also account for both the consumer surplus and TOC profits in their objective function. Therefore, when competition is strong (low road toll), early investments are more preferable than late investments. Low transportation cost combined with early adaptation stimulate the port demands, therefore increasing the TOC and port profits. However, high road toll combined with late adaptation have opposite effects on the port demands. As a matter of fact, large transportation cost increases the full costs paid by the shippers, while the absence of facility protection may cause the shippers to loose confidence on the ports in the first period. This results in decrease in demands over the two periods. This also leads to a small difference between the impacts of early and late adaptation on discounted welfare. If the public ports can even accumulate information over time, then postponing the investment to the next period may be the best option. This finding remains valid when port A invests in the first period and port B in the second period. Specifically, undertaking early adaptation always appears to be the best solution when ports invest at different times, except when there is neither information accumulation nor competition. In the absence of competition, the port has no incentives to invest early, though postponing the adaptation to the next period also presents

no additional benefits without information gain. In this case, the investment decisions of the ports will depend on the other variables.

The impacts of occurrence disaster occurrence probability and maximum possible damage are also similar to the private case. The higher the disaster occurrence probability (or the maximum damage), the broader the adaptation investments are. With low probability, the public ports are better off postponing the adaptation until the next period. Even when the investments are made at different times, the PA that invests late receives higher benefits than the one that does early. When the port facilities are highly vulnerable to natural disasters, it is optimal to invest in adaptation as early as possible, irrespective of the nature of the investment decisions (made simultaneously or at different times). Though information accumulation can increase the welfare associated with late investments, early investments will still bring higher benefits to the shippers, TOCs and PAs.

The shippers' potential disaster losses have clear impacts on the discounted welfare. For low value of γ, there is a very little difference between the effects of early and late investments on welfare (the public PAs appear to be indifferent between investing early and waiting). However, when the shippers bear a high proportion of the adaptation costs, it is optimal to invest earlier rather than later, even with information accumulation. The same reasoning applies to both simultaneous and separate investment decisions.

Again, the maintenance cost appears to have little influence on the investment decisions of the public PAs, though information accumulation increases the discounted welfare associated with late investments. Nevertheless, it is always optimal to invest earlier rather than later. Finally, the influence of discount factor on discounted welfare is more apparent for the public PAs than for the private ports. With low discount factor, there is a small difference between the welfare associated with early and late investments. When the discount factor is larger, early investments become a better option than the late ones, even with information gain.

In the next section, we discuss the implications for social welfare.

5. Implications for social welfare

Consider a central planner that chooses adaptation investments $\mathbf{I^w}$ and port quantities $\boldsymbol{q^{w,T}}$ at each period so as to maximize social welfare. Social welfare includes the surpluses of shippers, TOC and port profits over the two periods, along with the external benefits of the surrounding areas for having disaster adaptation facilities. The social welfare function is given by:

$$SW(\boldsymbol{q^{w,T}},\mathbf{I^w}) = SW^i + k\, SW^{ii} = \sum_{j=A,B}(CS_j^i + \pi_j^i + \Pi_j^i + \delta I_{j,1}) + k(CS_j^{ii} + \pi_j^{ii} + \Pi_j^{ii} + \delta I_{j,2}), \quad j = A, B, \tag{35}$$

where

$$SW^T = \frac{1}{8}\Big[-3t(q_A^T)^2 - 3t(q_B^T)^2 + q_A^T(8V + 4t - 8C_A^{S,T}) + q_B^T(8V + 4t - 8C_B^{S,T}) - 2tq_A^Tq_B^T\Big] - \frac{t}{2} - C_A^T - C_B^T,$$

where SW denotes social welfare, CS_j^T is the surplus of shippers using port j during period T obtained in (9), π_j^T and $\mathbf{\Pi}_j^T$ are, respectively, the corresponding TOC and PA profits, q_A^T and q_B^T are the (equilibrium) quantities, $C_j^{S,T}$ denotes the expected disaster losses for shippers and C_j^T is the adaptation cost for PA j. We introduce a positive parameter δ in (35) to capture the positive spillover effects from the adaptation investments on the other sectors of economy. It is reasonable to assume that if the ports invest in adaptation, for example by building storm barriers to prevent storm surges, the surrounding areas of the ports will also benefit from that protection. The condition $\delta > 0$ states that there is a positive link between the investments and regional welfare.

To ensure comparability of results, we keep the assumption that the port authorities have *naive expectations*.[46] The FOCs of (35) with respect to quantity $\boldsymbol{q^{w,T}} = (q_A^{w,T}, q_B^{w,T})$ give:[47]

$$\frac{\partial SW^T}{\partial q_j^{w,T}} = \frac{1}{4}(2t + 4V - 4C_j^{S,T} - 3tq_j^{w,T} - tq_{-j}^{w,T}) = 0, \quad j = A, B, \quad T = i, ii. \tag{36}$$

By solving the FOCs in (36) with respect to $\boldsymbol{q^{w,T}}$, we obtain the socially optimal quantities:

$$q_A^{w,T} = \frac{1}{2t}\left(t + 2V - 3C_A^{S,T} + C_B^{S,T}\right); \quad q_B^{w,T} = \frac{1}{2t}\left(t + 2V + C_A^{S,T} - 3C_B^{S,T}\right), \tag{37}$$

where $C_j^{S,T}$ is the shippers' expected losses, which vary according to the investment timing.

If both PAs invest at the beginning of the first period, the FOCs w.r.t. investments $\mathbf{I^w}$ give:

$$\frac{\partial SW}{\partial I_j^w} = \bar{\theta}_1^j(I_j^w)\left[\gamma\left(q_j^{w,i} + kq_j^{w,ii}\right) + (1+k)\right] - (1 + k\beta) + \delta = 0, \quad j = A, B,$$

[46] See Section 3 for more details about this assumption.

[47] The second order conditions with respect to quantity are satisfied when we assume $t > 0$ since $\partial^2 SW^T/\partial(q_j^T)^2 = -3t/4$ for $j = A, B$, confirming that we have a maximum.

where $q_j^{w,i}$ and $q_j^{w,ii}$ are the socially optimal quantities in (37). By rearranging the FOCs and using the same notation as in (23), we characterize the socially optimal adaptation investments by the following equations:

$$I_{A,1}^w = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta-\delta}{m_A^w(\mathbf{I_1^w})}\right]}; \quad I_{B,1}^w = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta-\delta}{m_B^w(\mathbf{I_1^w})}\right]}, \quad \text{where}$$

$$m_j^w(\mathbf{I_1^w}) = \gamma\left(q_j^{w,i} + kq_j^{w,ii}\right) + (1+k), \quad j = A, B. \tag{38}$$

To guarantee interior solutions, investment efficiency θ_1 needs to satisfy the condition: $\theta_1 \leq F_1^{-1}\left[\frac{1+k\beta-\delta}{m_j^w(\mathbf{I_1^w})}\right]$ for all $\theta \in [0, \theta_{\max}]$ and $j = A, B$. The corresponding social welfare comes from replacing $\mathbf{q^T}$ with $\mathbf{q^{w,T}}$ and $\mathbf{I} = (I_A, I_B)$ with $\mathbf{I_1^w} = (I_{A,1}^w, I_{B,1}^w)$, yielding:

$$SW(\boldsymbol{q}^{\mathbf{w},\boldsymbol{T}}, \mathbf{I_1^w}) = SW^i(\mathbf{q^{w,i}}, \mathbf{I_1^w}) + k\, SW^{ii}(\mathbf{q^{w,ii}}, \mathbf{I_1^w}). \tag{39}$$

If both ports undertake late investments, the FOCs with respect to $\mathbf{q^{w,T}}$ are similar to (37) where $T = \{i, ii\}$, except for the potential disaster losses for shippers. Specifically, the loss function for shippers $C_j^{S,T}$ is replaced by γDx when $T = i$ and by (25) when $T = ii$. The FOCs w.r.t. adaptation investments $\mathbf{I_2^w}$ lead to:

$$\frac{\partial SW}{\partial I_j^w} = k\bar{\theta}_2^j(I_j^w)\left(\gamma q_A^{w,ii} + 1\right) - k + k\delta = 0, \quad \text{where} \quad j = A, B, \tag{40}$$

where $q_j^{w,ii}$ is the socially optimally quantity obtained in (37).[48] By rearranging the FOCs and using the same notation as in (23), we characterize the socially optimal late investments by the following implicit functions:

$$I_{A,2}^w = \frac{Dx}{F_2^{-1}\left[\frac{1-\delta}{\bar{m}_A^w(\mathbf{I_2^w})}\right]}; \quad I_{B,2}^w = \frac{Dx}{F_2^{-1}\left[\frac{1-\delta}{\bar{m}_B^w(\mathbf{I_2^w})}\right]}, \quad \text{where}$$

$$\bar{m}_j^w(\mathbf{I_2^w}) = \gamma q_A^{w,ii} + 1, \quad j = A, B. \tag{41}$$

For an interior solution, variable θ_2 needs to satisfy $\theta_2 \leq F_2^{-1}\left[\frac{1-\delta}{\bar{m}_j^w(\mathbf{I_2^w})}\right]$ for all $\theta \in [0, \theta_{\max}]$ and $j = A, B$. The corresponding social welfare function is given by:

$$SW(\boldsymbol{q}^{\mathbf{w},\boldsymbol{T}}, \mathbf{I_2^w}) = SW^i(\mathbf{q^{w,i}}, \mathbf{I_2^w}) + k\, SW^{ii}(\mathbf{q^{w,ii}}, \mathbf{I_2^w}). \tag{42}$$

If port A (or port B) invests early and its rival (port A) undertakes late investments, then like the previous case, investments are not chosen simultaneously but assumed to be exogenous. The social welfare function is determined by the following equation:

$$SW(\mathbf{q^{w,i}}, \mathbf{q^{w,ii}}, I_{A,1}^w, I_{B,2}^w) = SW^i(\mathbf{q^{w,i}}, I_{A,1}^w) + k\, SW^{ii}(\mathbf{q^{w,ii}}, I_{B,2}^w). \tag{43}$$

In Eq. (43), SW^i depends on $I_{A,1}^w$ and SW^{ii} on $I_{B,2}^w$; quantities $\mathbf{q^{w,i}}$ and $\mathbf{q^{w,ii}}$ have the same expressions as in (37), except for the shippers' disaster losses functions.

To analyze the implications of the early and late adaptation investments for regional economy, we compare the social welfare functions in (39), (42) and (43). We proceed in the same way as in the previous analyses and conduct numerical simulations using the parameter values provided in Table 2 and similar scenarios as for the cases of private and public ports. The simulation results for early and late investments by the social planner are presented in Fig. A.9–A.11 in Appendix A.8.

In most cases, our simulation results indicate that early investments always lead to higher (discounted) social welfare than late investments. Moreover, information accumulation decreases socially optimally adaptation size, while enhancing the total welfare associated with late investments. It is optimal for the society that the PAs invest in adaptation immediately when competition is intensified. This is true even when rivalry between ports is weak. Interestingly enough, the effect of information accumulation on social welfare is more apparent. Specifically, information gain increases the levels of social welfare, regardless of the competition level. Since information accumulation also impacts the shippers' expected disaster losses, thereby their surpluses, we can expect pronounced effects for the social welfare. The society is better off with late adaptation when the ports are less likely to be threatened by a disaster. Though immediate investments are recommended when the port facilities are highly vulnerable to extreme weather and natural disasters. This reasoning applies to any situations. Similarly, it is socially optimal to invest early if the shippers are highly sensitive to the consequences of the investment decisions of the PAs, whilst waiting may represent a better option if the expected disaster losses for the shippers are negligible. Finally, for any levels of maintenance cost and discount factor, and regardless of the level of information accumulation, the society will always benefit from early investments rather than late ones. These findings can be explained by the positive externalities generated by early adaptation to the other sectors, which outreach the effects of other parameters. These results hold, even when the port authorities invest at different times.[49]

[48] Note that the spillover benefit parameter is multiplied by k in (40) since the investments are made in the second period.

[49] The simulation results are not included in the paper to save space. They are available upon request.

6. Knightian uncertainty for the disaster occurrence probability

In this section, we discuss the implications for the modelling framework when we allow the climate change-related disaster occurrence to have a more general distribution in the first period. In reality, scientific knowledge about climate change is very limited at the early stage of adaptation. This implies that if the investment decisions are made early, there may be a large ambiguity and (Knightian) uncertainty in the occurrence of a disaster. To capture this ambiguity, we assume that the disaster occurrence probability is characterized by a Knightian uncertainty (Knight, 1921) during the first period.[50] More specifically, the decision-makers are facing a set of probability measures rather than a single probability one when making the irreversible investment decisions (Nishimura and Ozaki, 2007). Hence, the disaster occurrence is assumed to be a Bernoulli trial with occurrence probability x over the support $[\underline{x}, \bar{x}]$. The probability density distribution of x during the first period is $p(x)$ and its cumulative distribution function $P(x)$. The mean and variance of x are denoted by μ_x and Σ_x, respectively. In the second period, the decision-makers acquire better knowledge of the climate change effects and related disasters, and this information accumulation leads to the realization of x.[51] Therefore, if the ports invest in the second period, they have more knowledge of the investment efficiency and disaster occurrence probability. We suppose that the disaster occurrence probability x is independent of the investment efficiency θ_h.[52]

The implications for the timing of the game are the following. If the port authorities invest in the first period ($T = i$), they simultaneously choose adaptation investments $\mathbf{I_1^x} = (I_{A,1}^x, I_{B,1}^x)$ and quantities $\mathbf{q_1^{ix}} = (q_A^{ix}, q_B^{ix})$, given the uncertainties of x and of investment efficiency θ_1 during the first period. In the second period ($T = ii$), the port authorities compete in quantities. In fact, x is realized when the port authorities simultaneously choose $\mathbf{q_1^{iix}} = (q_A^{iix}, q_B^{iix})$. If the port authorities make late investments, they compete in quantities in the first period, knowing that x is uncertain. In the second period, they simultaneously choose adaptation investments and quantities based on the distribution of investment efficiency θ_2 and disaster occurrence probability x_{ii} (hereafter, we denote x_{ii} the realization of random variable x in the second period). In this section, we focus on the case of private ports (parameter $\alpha = 0$) and state the difference with the public ports when necessary.

The maximization problem of port authority j under the Knightian uncertainty is:

$$\max_{\{I_j^x,\ q_j^{ix},\ q_j^{iix}\}} E_x[\Pi_j] = E_x[\Pi_j^i + k\Pi_j^{ii}] = E_x[\Pi_j^i] + kE_x[\Pi_j^{ii}] = \int_x \Pi_j^i\ p(x)\ dx + k\int_x \Pi_j^{ii}\ p(x)\ dx,$$
$$\text{where} \quad \Pi_j^T = f_j^T(\mathbf{q}^{Tx})\ q_j^{Tx} - C_j^{Tx}, \quad j = A, B, \quad T = i, ii, \quad \text{and}$$

$f_j^{Tx}(\mathbf{q}^{Tx})$ is the (inverse) demand function facing port authority j at period T given by Eq. (12). Note that we add superscript x on each variable to differentiate it with the case where x is treated as a fixed parameter. Under the assumption of Knightian uncertainty of x, the port authorities simultaneously choose investments and quantities so as to maximize expected intertemporal profits. The adaptation costs for the ports, C_j^{Tx}, also account for the uncertainty of x during the first period. Recall the expressions of the adaptation costs in Table 1 and assume that $x|\theta_h > I_j/D$, where $x|\theta_h$ is a ratio distribution. This is equivalent to assume $\theta_h < Dx/I_j$ or $x > \theta_h I_j/D$ for $T = \{i, ii\}$ and $h = \{1, 2\}$. We keep this assumption for the rest of this section.

The adaptation costs for ports associated with early investments are:

$$C_{j,1}^{ix} = E_x E_\theta[I_j + Dx - \theta_1 I_j] = \int_x \int_{\theta_1} (I_j + Dx - \theta_1 I_j)\ g_1(\theta_1)\ p(x)\ d\theta_1\ dx,$$
$$C_{j,1}^{iix} = k\ [\beta I_j + Dx_{ii}\ G_1^j(I_j) - \bar{\theta}_1^j(I_j)\ I_j], \quad \text{where} \quad \theta_1 < \frac{Dx}{I_j} \quad \text{and} \quad x > \frac{\theta_1 I_j}{D}.$$

Solving the above integrands, we obtain:

$$C_{j,1}^{ix} = I_j\ P_j + D\ \bar{\mu}_x^j(I_j)\ G_1^j(I_j) - \bar{\theta}_1^j(I_j)\ I_j\ P_j, \tag{44}$$

$$C_{j,1}^{iix} = k\ [\beta I_j + Dx_{ii}\ G_1^j(I_j) - \bar{\theta}_1^j(I_j)\ I_j], \quad \text{where} \quad \theta_1 < \frac{Dx}{I_j} \quad \text{or} \quad x > \frac{\theta_1 I_j}{D}, \tag{45}$$

where G_1^j and $\bar{\theta}_1^j$ are the cdf and conditional mean of θ_1, respectively, defined in (16); P_j is the cdf of x and $\bar{\mu}_x^j$ denotes its conditional mean. They are given by:

$$P_j = \int_x p(x)dx, \quad \bar{\mu}_x^j(I_j) = \int_x x\ p(x)\ dx \quad \text{for all} \quad x > \frac{\theta_1 I_j}{D}.$$

[50] A Knightian uncertainty in decision-making occurs when the relevant distribution probabilities of a variable are unknown to the decision-makers.

[51] We make this simplification for tractability purpose. Otherwise, it is possible to assume that in the second period, x has the same probability distribution, but with lower variance.

[52] This assumption indicates that the joint distribution of the two variables, x and θ_h, can be rewritten as the product of $p(x)$ and $g_h(\theta_h)$.

The port adaptation costs associated with late investments give:

$$C^{ix}_{j,2} = D\ E_x[x] = D\bar{\mu}^j_x,$$

$$C^{iix}_{j,2} = k\ [I_j + Dx_{ii}\ G^j_2(I_j) - \bar{\theta}^j_2(I_j)\ I_j], \quad \text{where} \quad \theta_2 < \frac{Dx}{I_j} \quad \text{or} \quad x > \frac{\theta_2 I_j}{D}. \tag{46}$$

Details of the calculations are provided in Appendix B.3. In our dynamic setting and under the assumption of naive expectations (see. Section 3 for details), the quantities set by the port authorities in the first period are the solutions of a single-period Cournot game. Therefore, $\mathbf{q}^{\mathbf{ix}*} = (q^{ix*}_A, q^{ix*}_B)$ is the solution of the following maximization problem:

$$\max_{\mathbf{q}^{ix}} E_x[\Pi_j] = \int_x f^i_j(\mathbf{q}^{ix})\ q^{ix}_j\ p(x)dx - C^{ix}_j, \quad \text{where} \quad j = A, B, \tag{47}$$

and $f^i_j(\mathbf{q}^{ix})$ is the (inverse) demand function facing port authority j in the first period, which is given by:

$$f^i_j(\mathbf{q}^{ix}) = \frac{1}{4}\left[2(t+2V) - 4C^{S,i}_j - 6t\ q^{ix}_j - t\ q^{ix}_{-j}\right], \quad j = \{A, B\}. \quad T = i, ii,$$

where $C^{S,i}_j = \gamma\ E_\theta[Max\{Dx - \theta_h I_j, 0\}]$. Using the Leibniz integral rule, the first order conditions of (47) with respect to $\mathbf{q}^{\mathbf{ix}} = (q^{ix}_A, q^{ix}_B)$ give:[53]

$$\frac{\partial E_x[\Pi_j]}{\partial q^{ix}_j} = \frac{1}{4}\left[(2t+4V)P_j - 12t\ q^{ix}_j P_j - t\ q^{ix}_{-j} P_j - 4\bar{C}^{S,ix}_j\right] = 0, \quad j = A, B, \tag{48}$$

where $\bar{C}^{S,ix}_j = \int_x C^{S,i}_j\ p(x)\ dx$ for all $x > \theta_h I_j / D$. The solution of Eq. (48) for $\mathbf{q}^{\mathbf{ix}} = (q^{ix}_A, q^{ix}_B)$ is:

$$q^{*ix}_j = \frac{2}{143t}\left[11(2V+t) - \frac{24}{P_j}\ \bar{C}^{S,ix}_j + \frac{2}{P_{-j}}\ \bar{C}^{S,ix}_{-j}\right], \quad j = A, B, \quad j \neq -j. \tag{49}$$

The Knightian uncertainty of x leads the port authorities to account for the weighted average losses of shippers at both ports (with weights being equal to $1/P_j$ and $1/P_{-j}$) rather than the generalized shippers' costs when setting the quantities in the first period.[54] We have shown in Section 3.2.1 that, under the assumption of naive expectations, the quantities set by the ports in the second period ($T = ii$) are determined by certain adjustment processes, which are given by Eqs. (19) and (20), i.e.,

$$q^{iix}_A = \frac{1}{12t}\left(tq^{ix}_B + 4V + 2t - 4\ C^{S,iix}_A\right), \quad q^{iix}_B = \frac{1}{12t}\left(tq^{ix}_A + 4V + 2t - 4\ C^{S,iix}_B\right). \tag{50}$$

Quantity q^{*ix}_j is given by (49) and the expressions for $C^{S,iix}_j$ can be obtained directly from (45) and (46). Specifically, we can easily show that the disaster loss functions for the shippers associated with early investments give:

$$\bar{C}^{S,ix}_{j,1} = \gamma\left[D\ \bar{\mu}^j_x(I_j)\ G^j_1(I_j) - \bar{\theta}^j_1(I_j)\ I_j\ P_j\right], \quad \bar{C}^{S,iix}_{j,1} = \gamma\left[D\ x_{ii}\ G^j_1(I_j) - \bar{\theta}^j_1(I_j)\ I_j\right].$$

For the case of late investments, the disaster losses for the shippers yield:

$$\bar{C}^{S,i}_{j,2} = \gamma D\ E_x[x] = \gamma D\bar{\mu}^j_x, \quad \text{and} \quad \bar{C}^{S,ii}_{j,2} = \gamma\left[D\ x_{ii}\ G^j_2(I_j) - \bar{\theta}^j_2(I_j)\ I_j\right]. \tag{51}$$

Contrary to the previous analysis, the (equilibrium) quantities are not similar across periods because not only the investment efficiencies vary across periods, but also the disaster occurrence probability becomes unknown to the port authorities when they are making the quantity decisions in the first period.

If both ports invest in the first period, the first order conditions with respect to adaptation investments $\mathbf{I}^{\mathbf{x}}_{\mathbf{1}} = (I^x_{A,1}, I^x_{B,1})$ are given by:

$$\begin{aligned}\frac{\partial E_x[\Pi_j]}{\partial I^x_j} &= \frac{1}{4}\frac{\partial}{\partial I^x_j}\int_{\theta_1 I^x_j/D}^{\bar{x}}\{[2(t+2V) - 4C^{S,ix}_j - 6t\ q^{*ix}_j - t\ q^{*ix}_{-j}]\ q^{*ix}_j \\ &\quad + k[2(t+2V) - 4C^{S,iix}_j - 6t\ q^{*iix}_j - t\ q^{*iix}_{-j}]\ q^{*iix}_j\}\ p(x)\ dx \\ &\quad - \frac{\partial}{\partial I^x_j}\left[D\ G^j_1(\bar{\mu}^j_x + kx_{ii}) - \bar{\theta}^j_1(I^x_j)(P_j + k)\ I^x_j\right] - (P_j + k\beta) = 0,\end{aligned} \tag{52}$$

where $j = A, B$. The adaptation investments chosen by the ports in the beginning of the first period are the solutions of (52), which satisfy the constraints on the random variables, $x > \theta_1 I^x_j / D$, and the second order conditions.[55]

[53] The second order conditions are satisfied for a maximum.

[54] In Eq. (49), we can interpret $1/P_j$ and $1/P_{-j}$ as the weights and $\bar{C}^{S,i}_j(x)$ the average disaster loss for shippers.

[55] The explicit forms of the second order conditions are difficult to obtain without the specifications of the functional form of the probability distributions of x and θ_1. However, we have verified them gradually along the simulation exercises.

If the ports invest in the second period, the quantities set in the second period are determined by (50), with θ_1 and $C^{S,iix}_{j,1}$ replaced with θ_2 and $C^{S,iix}_{j,2}$, respectively. The adaptation investments $\mathbf{I^x_2} = (I^x_{A,2}, I^x_{B,2})$ are the solutions of the following first order conditions:[56]

$$\begin{aligned}\frac{\partial E_x[\Pi_j]}{\partial I_j} &= \frac{1}{4}\frac{\partial}{\partial I_j}\int_x \left[(2t+4V-4C^{S,i}_j - 6t\ q^{*ix}_j - t\ q^{*ix}_{-j})\ q^{*ix}_j\ p(x)\ dx\right] \\ &\quad + \frac{k}{4}\frac{\partial}{\partial I_j}\left[(2t+2V-4C^{S,ii}_j - 6t\ q^{*iix}_j - t\ q^{*iix}_{-j})\ q^{*iix}_j\right] \\ &\quad - \frac{\partial}{\partial I_j}\left[D\bar{\mu}^j_x + k\ [I_j + Dx_{ii}\ G^j_2(I_j) - \bar{\theta}^j_2(I_j)\ I_j]\right] = 0, \end{aligned} \tag{53}$$

where the expected disaster losses for shippers are given by (51). Note that the loss function in the first period no longer depends on I_j because no investments are made in that period. The quantities set by the port authorities in the first period are the solutions of the single-period Cournot game in (47).

The solutions of Eqs. (52) and (53) require the specifications of the functional forms of the distributions of disaster occurrence probability x and investment efficiency θ_h for $h = 1, 2$, since term I^x_j appears both implicitly and explicitly in almost each component of the equations. Therefore, the analytical solutions can be hard to obtain. Nevertheless, in the section, we provide the framework for implementing the simulation exercises and empirical analyses.

7. Conclusions

In this paper, we propose an analytical framework to investigate the size and timing of adaptation investment to climate change effects for ports under uncertainty in a competitive market. We develop a two-period real options game model in which two port authorities (PA) compete in quantities at the upstream level and two terminal operator companies (TOC) (one at each port) downstream. Specifically, the PAs choose adaptation investments at the beginning of either the first or the second period, taking into account the uncertainty of investment efficiency, information accumulation between the periods and the market conditions. We assume that waiting allows the decision-makers to accumulate information and better knowledge of the adaptation projects, climate change and related disasters. This information accumulation leads to greater investment efficiency in the next period. In terms of probability, the distribution of efficiency of late adaptation investments is as large as the distribution of efficiency of early investments in the sense of *First- degree Stochastic Dominance*. This paper contributes to the existing literature, by (i) considering efficiency of investment as uncertain, (ii) incorporating stochastic dominance approach into a discrete-time real options game setting so as to capture the effects of information accumulation on investment and pricing decisions of ports, and (iii) by introducing into the model framework a Knightian uncertainty (Knight, 1921) for the disaster occurrence probability.

We find that the optimal timing of investment is significantly influenced by the disaster occurrence probability, information gain over time and the level of port competition. When competition is intensified, investing immediately appears to be the best option. However, early investments become less preferred when competition is weak, even lesser if the ports can accumulate better knowledge of the adaptation projects between the periods. The ports are also better off waiting until the next period to adapt when (*i*) the disaster occurrence probability is low, (*ii*) the shippers are less likely to be affected by the potential disasters, (*iii*) maintenance cost is very high, and (*iv*) discount factor is very low. Our results suggest that, in equilibrium, information accumulation decreases the adaptation size, while increasing the discounted welfare associated with late investments. These findings hold for both the private and public ports and for simultaneous investments by the PAs. Though, in most cases, the public PAs invest more than the private ones. For the cases of non-simultaneous investments, the PA with early investment always shows better outcomes than the one that waits, even with information accumulation. In most situations, the society would benefit more from early investments than from late investments because of the positive spillover effects generated by early adaptation on the surrounding areas of the ports and the local community.

The findings from this study emphasize the importance of accounting for competition and information accumulation in the investment decisions regarding climate change adaptation. In a competitive market, ports may use adaptation investment as a strategic variable for competing with each other. As a matter of fact, there are situations where ports have considered infrastructure projects, expansion or capital improvement, as opportunities for addressing competition in conjunction with climate change. This has been the case of Port of Gulfport that has elevated the entire port from 10 feet to 14 feet (initially planned to 25 feet) and has undertaken shore projection project and wharf upgrades in its 84-acre port expansion and restoration programs, so as to deal with competition and resilience issues. Massport has also planned to implement a resilience program, consisting of enhancing both near-term and long-term resilience of critical buildings and infrastructure, as an integrated part of the port's business strategy and operations. Another example is Port of

[56] Again, the solutions should satisfy the second order conditions, along with the conditions on θ_2 and x.

Philadelphia, which has begun to incorporate climate change adaptation into its future projects, such as the "Southport marine terminal development project". Nevertheless, uncertainty and lack of information about the adaptation projects, climate change and related disasters remain a significant hindrance to effective adaptation. In most cases, this has resulted in late investments. For instance, up to 2016, Port of Metro Vancouver has not developed any plans to tackle adaptation to climate change issues because of their inability to define or establish an appropriate approach. Since ports play a critical role in the local, regional and global economy, they have to remain efficient, functional, and most importantly, resilient in the near future. Therefore, one needs to create incentives for the decision-makers to invest in adaptation as early as possible.

To achieve this objective, the ports and all parties involved may want to invest more efforts in accumulating information and knowledge about the adaptation projects. In practice, some ports have incorporated information accumulation into their adaptation plans. In the US, Port of Wilmington's efforts on adaptation are focused on getting reliable information to support decisions and developing collaborative partnerships. Port of Oakland is pursuing a three-pronged assessment of the port's climate change and sea-level rise challenge, with a focus on building strategic partnership, gathering information from subject matter experts, and promoting inter-departmental coordination and information-sharing for purposes of presenting a recommended climate change strategy. Collaboration between decision-makers and stakeholders at the local, regional, state and national level is also required at the different stages of adaptation. For example, Port Authority of New York/New Jersey has worked closely with public and private entities owning or operating transportation infrastructure within the New York City metropolitan area to implement internal and external adaptation strategies, such as inventory and assessment of multi-hazard risk assessment, integration of climate resilience in the updated engineering design guidelines. Port of Tacoma has also collaborated with regional, local and federal partners on several ongoing adaptation projects, such as raising levees and creating setbacks for Lower Puyallup River, evaluating and modifying the design of future pier structures and related infrastructures in consideration of climate change and future sea level rise.

This study has some limitations. Given the complexities arising from the use of general distribution for the investment efficiency, we have turned to simulation exercises to derive the main insights of the paper. We have assumed a specific distribution (log normal) for the investment efficiency. Though simulation exercise combined with sensitivity analyses offer a good alternative when the model suffers from analytical tractability, the use of other general distributions can also be explored. Furthermore, the derivations of the analytical solutions for the model with Knightian uncertainty were challenging because we treat two random variables in a dynamic context. Though it would be a valuable future research topic. We also abstract away the free-ride problem to focus on the interaction between information accumulation, investment timing and competition. A natural extension of the model is to consider the free-ride issue. In such case, the adaptation costs can be shared between the TOCs, PAs, and stakeholders, along with multiple levels of government (local, regional and federal). Finally, the modeling framework can be extended to include multiple time periods and reversible investment.

Appendix A

A.1. Duopoly competition between ports

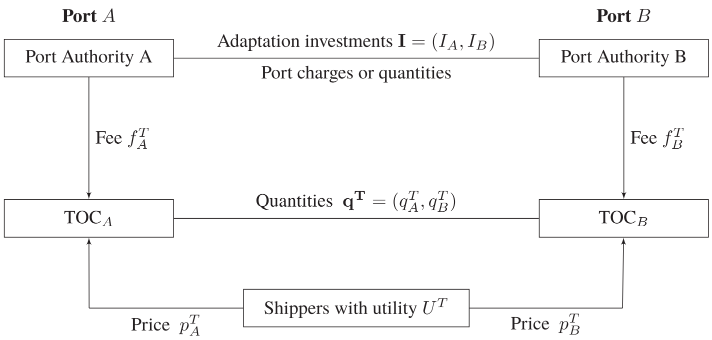

Fig. A.1. Duopoly competition between ports at period *T*.

A.2. Ports' Decisions and investment timing

Table A.1
Ports' investment decisions during the first and second period.

	(a) First period $T = i$ Port A			(b) Second period $T = ii$ Port A		
		Yes	No		No	Yes
Port B	Yes	(Yes, Yes)	(No, Yes)	Port B No	(No, No)	(Yes, No)
	No	(Yes, No)	(No, No)	Yes	(No, Yes)	(Yes, Yes)

Note: "Yes/No" refers to undertake immediate/late adaptation investments. The first component in the bracket indicates port A's decision and the second port B's decision, i.e. (Port A, Port B). For example, if both ports invest in the first period, then we have (Yes, Yes) in Table (a) and (No, No) in (b). This corresponds to the case in the third line and third column of each table. Alternatively, if A invests in the first period and B in the second period, then we get (Yes, No) in (a) and (No, Yes) in (b).

	First period $(T = i)$	Second period $(T = ii)$
A & B invest early	$(I_A, I_B), (q_A^i, q_B^i)$	(q_A^{ii}, q_B^{ii})
A & B invest late	(q_A^i, q_B^i)	$(I_A, I_B), (q_A^{ii}, q_B^{ii})$
A invests early & B waits	(I_A, q_A^i, q_B^i)	$(I_B, q_A^{ii}, q_B^{ii})$
A waits & B invests early	(I_B, q_A^i, q_B^i)	$(I_A, q_A^{ii}, q_B^{ii})$

Fig. A.2. Strategic decision variables and timing of the game over the two periods.

Table A.2
Summary of the analytical results.

Private ports		
Investment timing	Both in first period	Both in second period
Investment size	$I_{j,1}^* = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m_j^0(\mathbf{I_1^*})}\right]}$	$I_{j,2}^* = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}_j^0(\mathbf{I_2^*})}\right]}$
	$m_j^0 = \frac{144}{143}\gamma(q_j^{*i} + kq_j^{*ii}) + (1+k)$	$\bar{m}_j^0 = \frac{144}{143}\gamma q_j^{*ii} + 1$
Quantity	$q_j^{*T} = \frac{2}{143t}[11(2V+t) - 24C_j^{S,T} + 2C_{-j}^{S,T}]$	$q_j^{*ii} = \frac{2}{143t}[11(2V+t) - 24C_j^{S,ii} + 2C_{-j}^{S,ii}]$
at period T	$C_j^{S,T} = \gamma[Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)]$	$C_j^{S,i} = \gamma Dx,\ C_j^{S,ii} = \gamma[Dx\ G_2^j((I_j) - I_j\ \bar{\theta}_2^j(I_j)]$
Profits	$\Pi_{j,1}^* = f_j^{*i}\ q_j^{*i} + k\ f_j^{*ii}\ q_j^{*ii} - (1+k\beta)\ I_{j,1}^*$	$\Pi_{j,2}^* = (f_{j,2}^{*i}\ q_{j,2}^{*i} - Dx) + k\ \{f_{j,2}^{*ii}\ q_{j,2}^{*ii}$
	$-(1+k)[G_1^j(I_{j,1}^*) - I_{j,1}^*\ \bar{\theta}_1^j(I_{j,1}^*)]$	$-[I_{j,2}^* + Dx\ G_2^j(I_{j,2}^*) - I_{j,2}^*\ \bar{\theta}_2^j(I_{j,2}^*)]\}$
Public ports		
Investment timing	Both in first period	Both in second period
Investment size	$I_{j,1}^* = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m_j^1(\mathbf{I_1^*})}\right]}$	$I_{j,2}^* = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}_j^1(\mathbf{I_2^*})}\right]}$
	$m_j^1 = \frac{\gamma}{6t}[6t(q_j^{*i} + kq_j^{*ii}) - t(q_{-j}^{*i} + kq_{-j}^{*ii}) + 2V(1+k) - (C_{-j}^{S,i} + kC_{-j}^{S,ii})] + (1+k)$	$\bar{m}_j^1 = \frac{\gamma}{6t}\left(6tq_j^{*ii} - tq_{-j}^{*ii} + 2V - C_{-j}^{S,ii}\right) + 1$
Quantity	$q_j^{*T} = \frac{1}{3t}\left(4V + t - 5C_j^{S,T} + C_{-j}^{S,T}\right)$	$q_j^{*T} = \frac{1}{3t}\left(4V + t - 5C_j^{S,T} + C_{-j}^{S,T}\right)$
at period T	$C_j^{S,T} = \gamma[I_j + Dx\ G_1^j(I_j) - I_j\ \bar{\theta}_1^j(I_j)]$	$C_j^{S,i} = \gamma Dx,\ C_j^{S,ii} = \gamma[Dx\ G_2\left(\frac{Dx}{I_j}\right) - I_j\ \bar{\theta}_2^j(I_j)]$
Welfare	$W_{j,1}^* = (CS_{j,1}^{*i} + CS_{j,1}^{*ii}) + k(\pi_{j,1}^{*i} + \pi_{j,1}^{*ii})$	$W_{j,2}^* = \left(CS_j^{*i} + k\ CS_j^{*ii}\right) + \left(\pi_{j,2}^{*i} + k\ \pi_{j,2}^{*ii}\right)$
	$+[f_j^{*i}\ q_j^{*i} + k\ f_j^{*ii}\ q_j^{*ii} - (1+k\beta)\ I_j^* - (1+k)\ G_1^j(I_j^*) - I_j^*\ \bar{\theta}_1^j(I_j^*)]$	$+[f_j^{*i}\ q_j^{*i} - Dx + k\ f_j^{*ii}\ q_j^{*ii} - k(I_j^* - Dx\ G_2^j(I_j^*) - I_j^*\ \bar{\theta}_2^j(I_j^*))]$

A.3. Details and justification of the parameter choice

This section describes in detail the choice of parameters for the numerical exercise. We consider two scenarios with low ($x = 0.001\%$) and high ($x = 20\%$) disaster occurrence probability, and choose the moderate case ($x = 10\%$) as the baseline. In practice, the likelihood of occurrence for extreme events within the lifetime of the infrastructure can be classified into four categories, including low ($x \le 1\%$), moderate ($1\% < x \le 10\%$), high ($10\% < x \le 20\%$), and virtually certain or already occuring ($> 20\%$). For example, Becker et al. (2012) found that most ports in Europe, North America, and Oceania design their infrastructures to withstand an extreme event that has a 1% chance of occurring in any given year.

The time discount factor used in the context of transport infrastructure projects varies across regions. Specifically, each country independently sets the discount rate to be used for schemes in its territory.[57] We set a reasonable discount factor of $k = 0.5$, though it does not reflect real world. As for the maintenance costs (β), literature has identified a range of estimates of maintenance costs ranging from 0.3% and 1.1% of the initial construction costs for river dikes and sea dikes, respectively (see for example, Nicholls et al. (2010)). In this analysis, the maintenance cost represents 1% of the initial cost of the investment as a baseline and then test two different values: low (0.01%) and high cost (0.7%). The gross benefits of shippers V are normalized to 1.

We consider a potential damage cost of 1% (in percentage of GDP). According to the *Stern Review* (Stern, 2007), the damage costs of all extreme weather events could reach up to 1% of GDP by the middle of the century at the global level. For US only, the damage cost is estimated at 0.13% for hurricane and 0.01% – 0.03% for coastal flood and sea level rise while the cost of coastal damage in Europe ranges between 0.01 and 0.02%.[58] In Japan, Esteban et al. (2009) show that the increased frequency of wind events could reduce the potential Japanese GDP by between 1.5% and 3.4% by 2085 if the port planners do not take into consideration the potential future increase in storm intensity when designing port capacities and sea defences.

A.4. Decomposition of the adaptation cost for port j at period T

Recall the adaptation costs for port j at period T for the cases of early and late investment, respectively, as specified in (14) and (15):

$$C^{i}_{j,1} = I_j + E(Max\{Dx - \theta_1 I_j, 0\}), \qquad C^{ii}_{j,1} = k[\beta I_j + E(Max\{Dx - \theta_1 I_j, 0\})],$$
$$C^{i}_{j,2} = Dx, \qquad C^{ii}_{j,2} = k[I_j + E(Max\{Dx - \theta_2 I_j, 0\})].$$

The *Max* function can be decomposed as follows:

$$E(Max\{Dx - \theta_h I_j, 0\}) = \begin{cases} E(Dx - \theta_h I_j) = \int_0^{Dx|I_j} (Dx - \theta_h I_j) g_h(\theta) d\theta_h & \text{if} \quad \theta_h \le \frac{Dx}{I_j}, \\ 0 & \text{if} \quad \theta_h > \frac{Dx}{I_j}, \end{cases}$$

where $g_h(\theta)$ is the probability density function of θ_h with $h = \{1, 2\}$ and $j = \{A, B\}$. Solving the above integrand yields

$$E(Max\{Dx - \theta_h I_j, 0\}) = \begin{cases} Dx\ G^j_h(I_j) - \bar{\theta}^j_h(I_j)\ I_j & \text{if} \quad \theta_h \le \frac{Dx}{I_j}, \\ 0 & \text{if} \quad \theta_h > \frac{Dx}{I_j}, \end{cases}$$

where

$$\bar{\theta}^j_h(I_j) = \int_0^{Dx/I_j} \theta_h\ g_h(\theta)\ d\theta_h \quad \text{and} \quad G^j_h(I_j) = \int_0^{Dx/I_j} g_h(\theta) d\theta,$$

where $\bar{\theta}^j_h$ denotes the conditional mean of θ_h and G^j_h its associated CDF. Again, both $\bar{\theta}^j_h$ and G^j_h depend on I_j.

[57] For example, Odgaard et al. (2006) found that the discount rates for transport infrastructure project in Europe range from 3% to 8%, while Jones et al. (2014) identified that transport infrastructure projects on port extension and port entrance assume a discount rate of 4%.

[58] For example, in UK, the infrastructure damage costs of floods assuming no change in flood management to cope with rising risk are estimated to be around 0.2% – 0.4%.

A.5. Simulation results for private ports

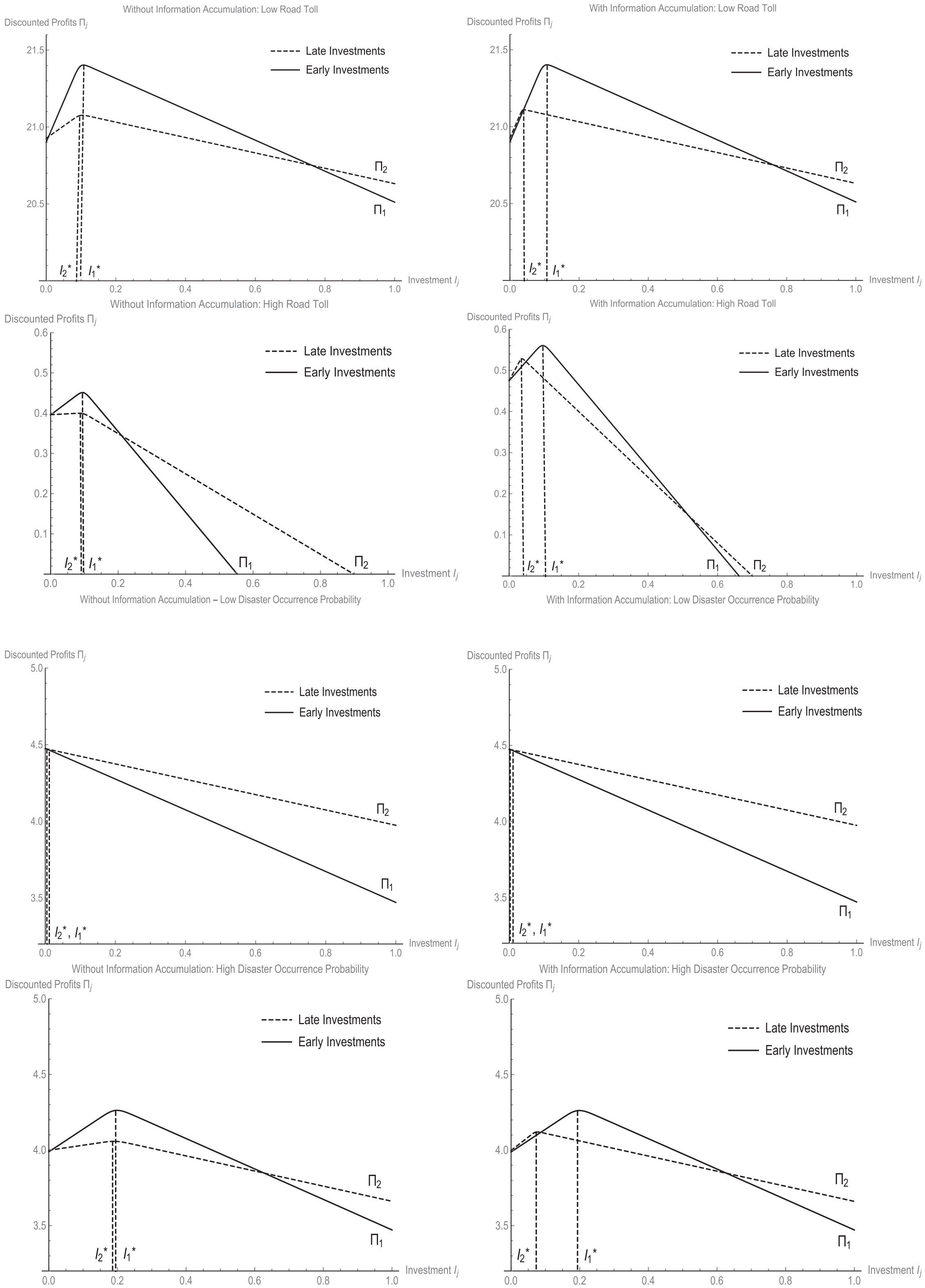

Fig. A.3. Impacts of parameters on discounted profits when investments are chosen simultaneously.

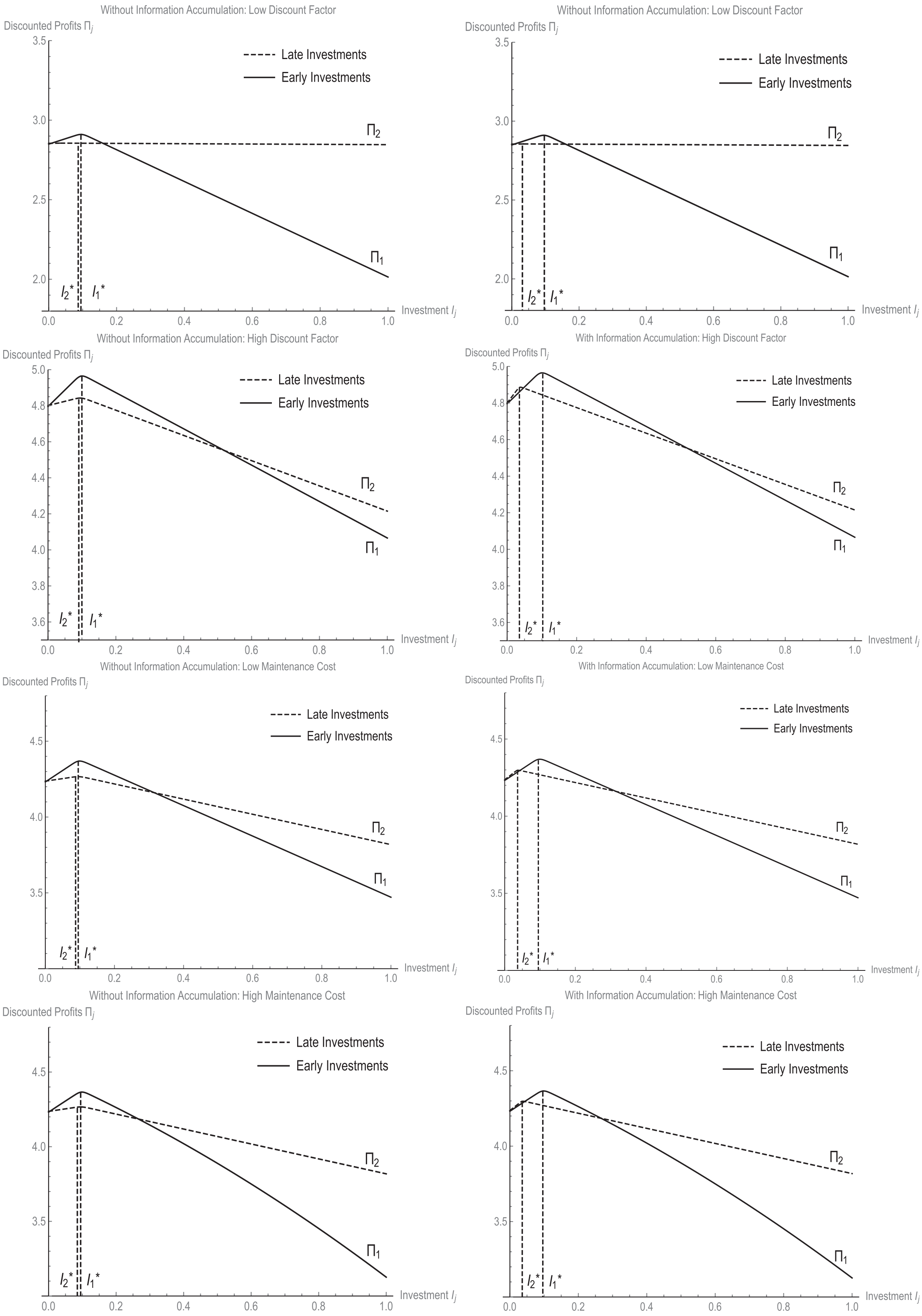

Fig. A.4. Impacts of parameters on discounted profits when investments are chosen simultaneously (cont'd).

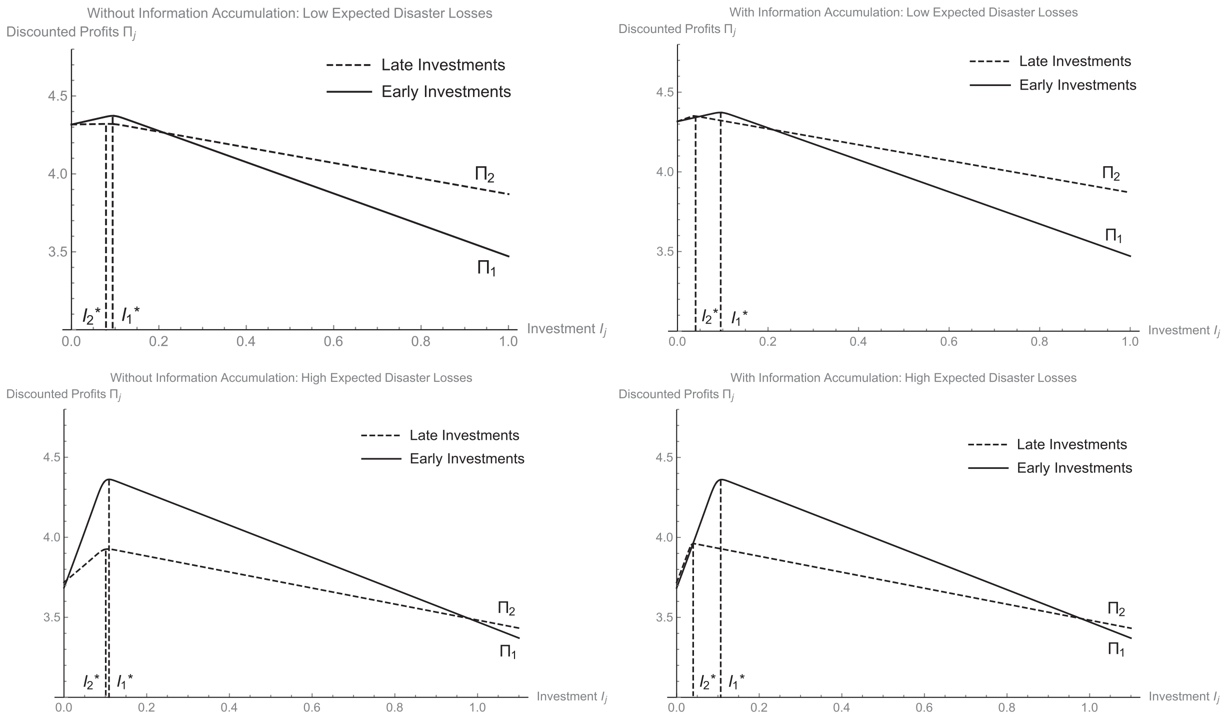

Fig. A.5. Impacts of parameters on discounted profits when investments are chosen simultaneously (cont'd).

A.6. Simulation results for public port authorities

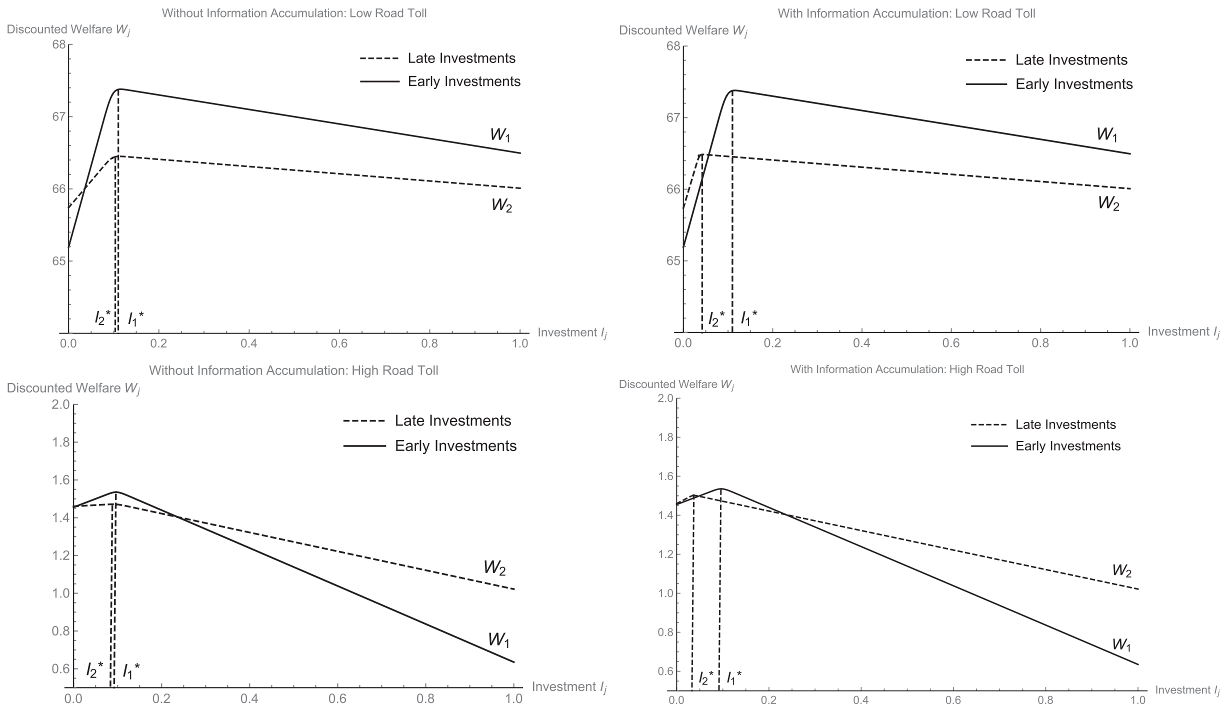

Fig. A.6. Impacts of parameters on discounted welfare when investments are chosen simultaneously.

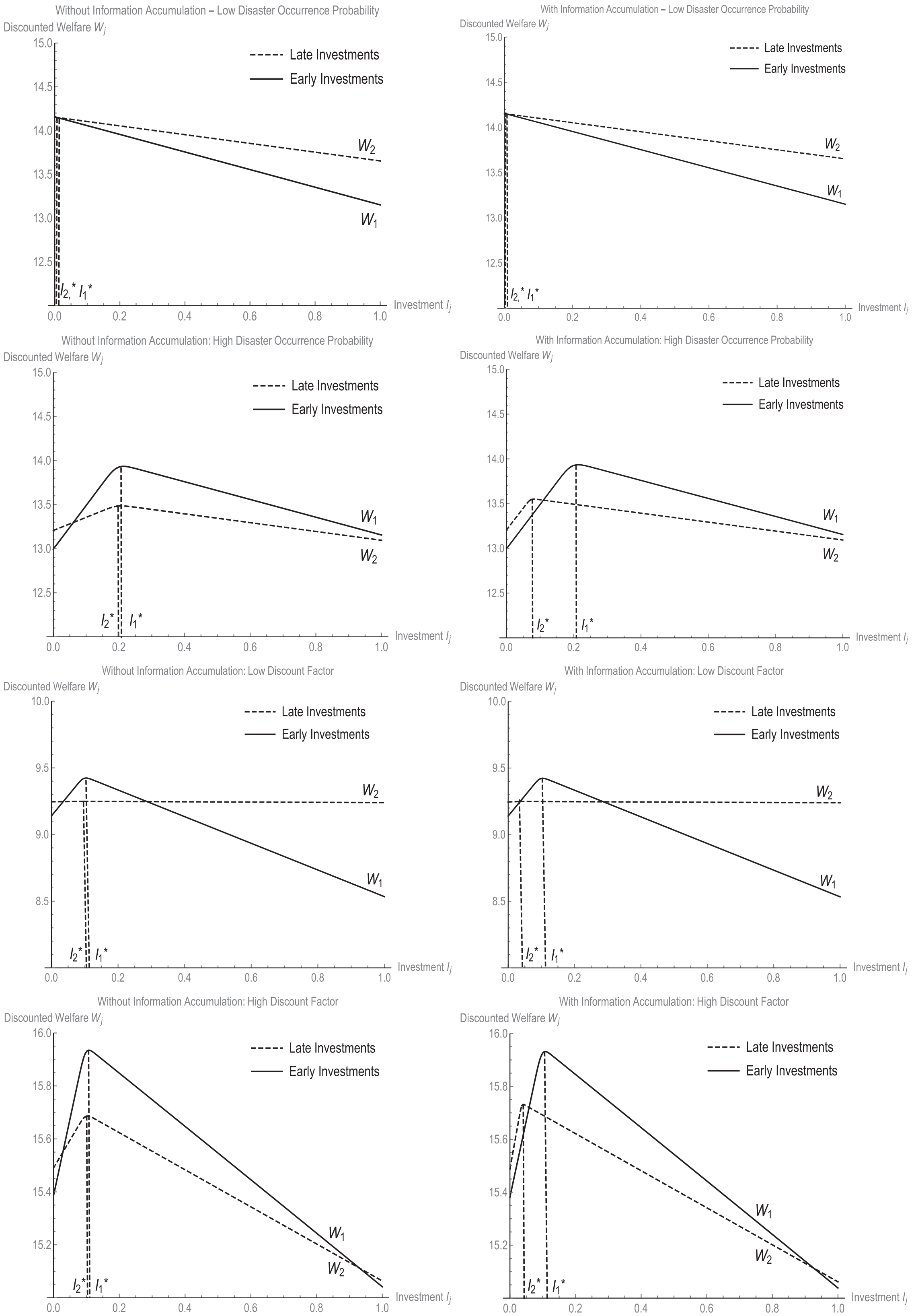

Fig. A.7. Impacts of parameters on discounted welfare when investments are chosen simultaneously.

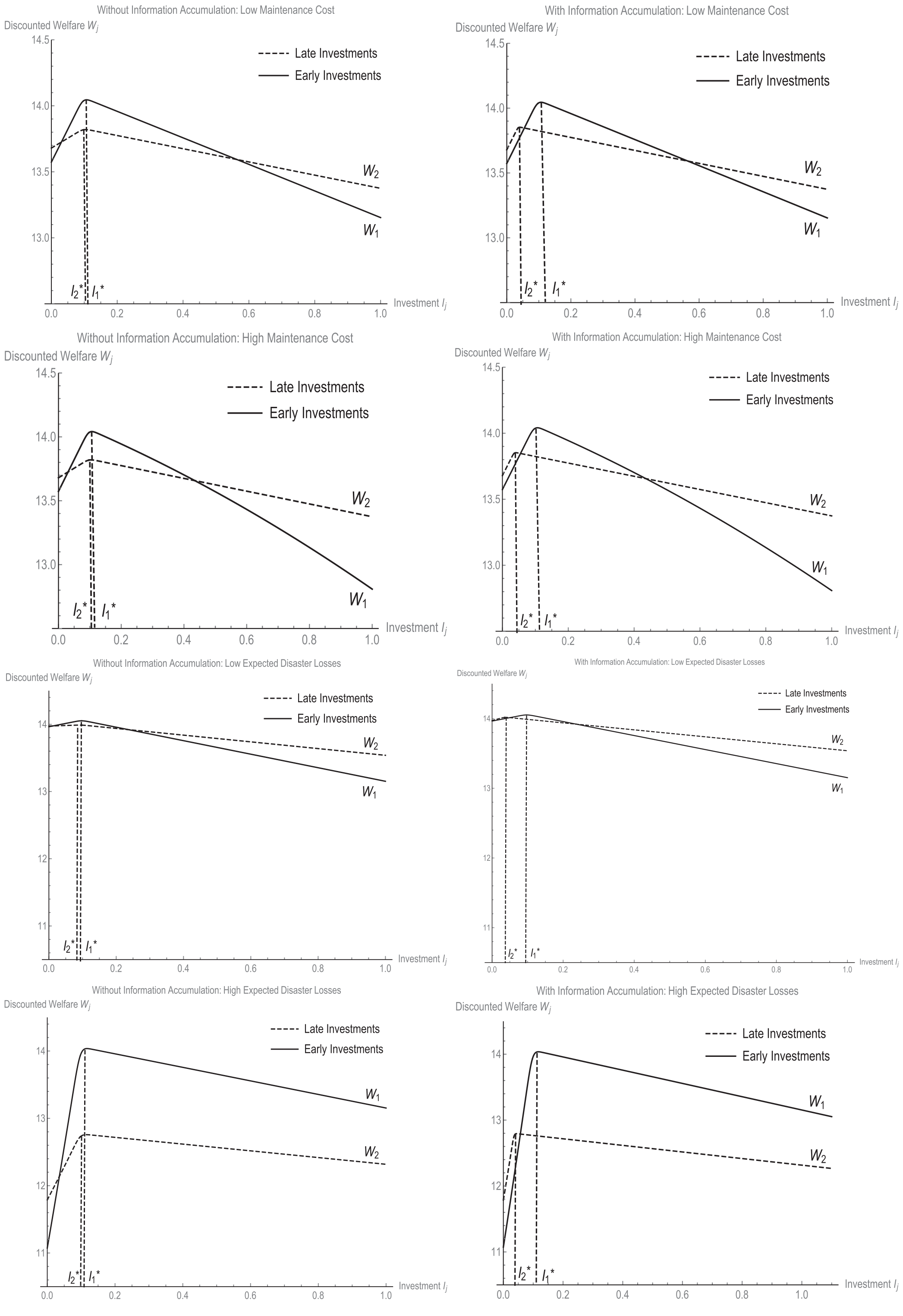

Fig. A.8. Impacts of parameters on discounted welfare when investments are chosen simultaneously (cont'd).

A.7. Derivations of consumer surplus

The surplus of shippers at each port is given by:

$$CS_A^T = \int_0^{|z^L|} \left(V - p_A^T - C_A^{S,T} - tz\right)dz + \int_0^{\tilde{z}} \left(V - p_A^T - C_A^{S,T} - tz\right)dz,$$

$$CS_B^T = \int_0^{1-\tilde{z}} \left(V - p_B^T - C_B^{S,T} - tz\right)dz + \int_0^{z^R-1} \left(V - p_B^T - C_B^{S,T} - tz\right)dz,$$

where $\tilde{z}$, z^L and z^R are defined in (2) and (3), and q_A and q_B are the port demands. Solving the above integrands leads to the consumer surplus function CS_A^T and CS_B^T, such that

$$CS_A^T = \frac{t}{16}\left[7(q_A^T)^2 - (q_B^T)^2 - 4q_A^T + 4q_B^T + 2q_A^T q_B^T - 4\right], \tag{A.1}$$

$$CS_B^T = \frac{t}{16}\left[7(q_B^T)^2 - (q_A^T)^2 - 4q_B^T + 4q_A^T + 2q_A^T q_B^T - 4\right], \quad \text{where} \quad T = i, ii. \tag{A.2}$$

The total consumer surplus for period T, denoted by CS^T, is the sum of the shippers' net benefit at each port, i.e. the sum of (A.1) and (A.2) and is given by

$$CS^T = \frac{t}{8}\left[3(q_A^T)^2 + 3(q_B^T)^2 + 2q_A^T q_B^T - 4\right], \quad \text{where} \quad T = i, ii.$$

A.8. Simulation results for social welfare

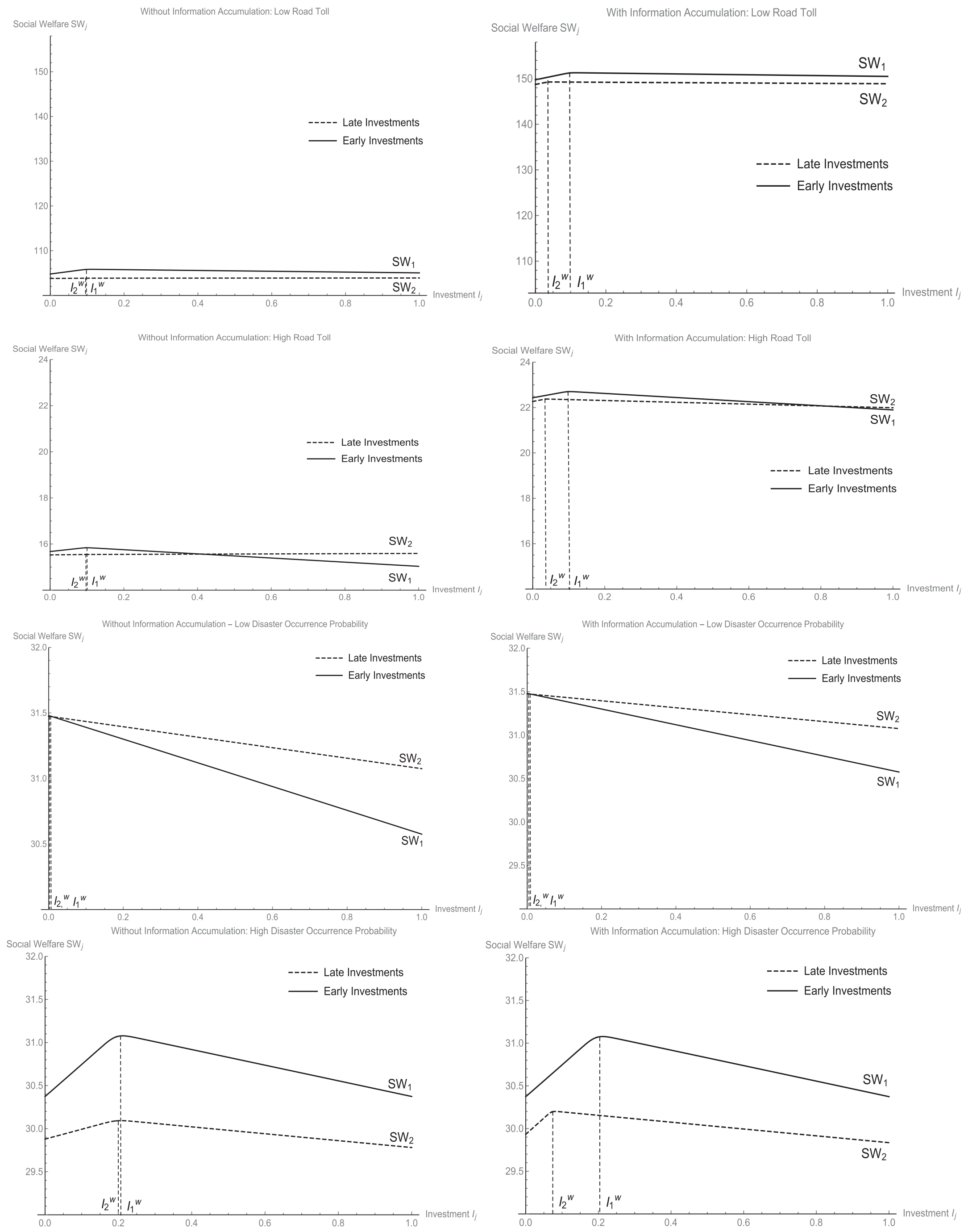

Fig. A.9. Social planner's investment decisions and social welfare.

A.9. Simulation results for social welfare

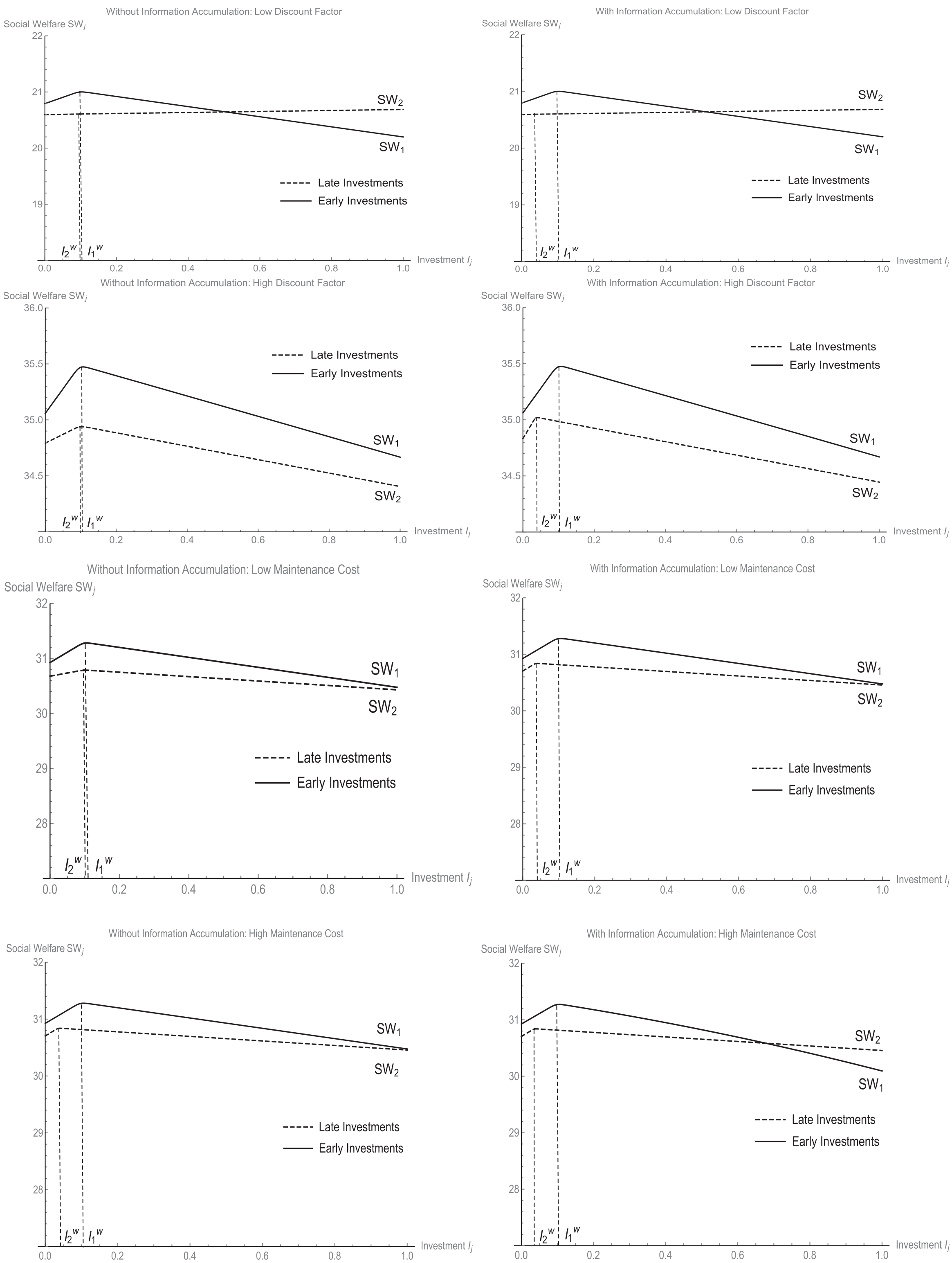

Fig. A.10. Social planner's investment decisions and social welfare.

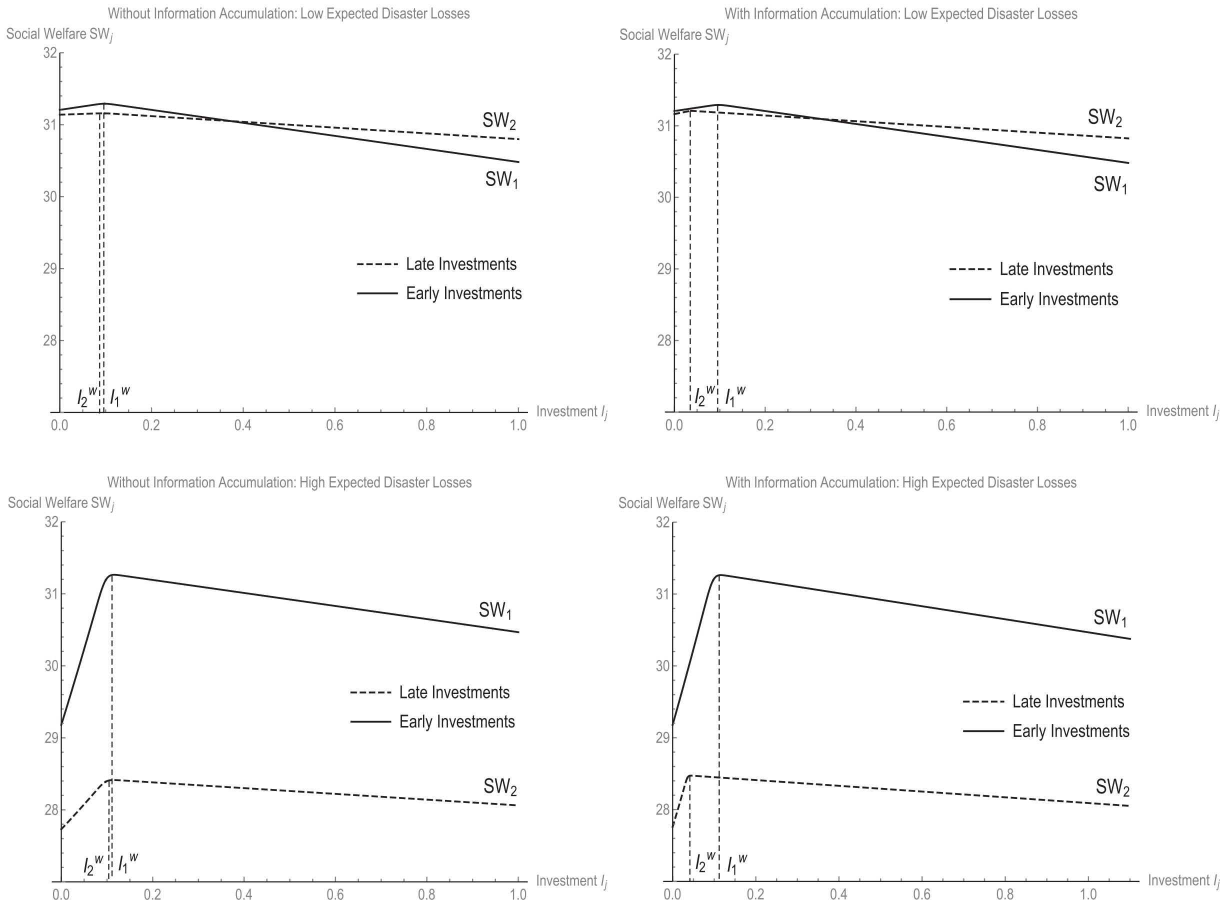

Fig. A.11. Social planner's investment decisions and social welfare (cont'd).

A.10. Price competition between ports

A.10.1. Fees and adaptation investments in equilibrium

For comparison purposes, we now assume that the private port authorities compete in price or port charges (Basso and Zhang, 2007; De Borger et al., 2008). Recalling the expressions of the quantity equilibrium of the terminal operators at period T obtained in (11), we have:

$$q_A^{*T} = \frac{2}{35t}\left[5(t+2V) - 12C_A^{S,T} + 2C_B^{S,T} - 12f_A^T + 2f_B^T\right], \tag{A.3}$$

$$q_B^{*T} = \frac{2}{35t}\left[5(t+2V) + 2C_A^{S,T} - 12C_B^{S,T} + 2f_A^T - 12f_B^T\right], \tag{A.4}$$

The maximization problem consists of choosing the fees at each period and adaptation investments so as to maximize the welfare function. That is:

$$\max_{I_j, f_j^i, f_j^{ii}} \; W_j = W_j^i + kW_j^{ii} \quad s.t. \quad f_{-j}^{ii} = f_{-j}^{i}, \quad \text{with} \quad j = A, B,$$

where W_j is the welfare function given in (13), the demand functions are given by (A.3) and (A.4), and the adaptation costs for ports remain unchanged, as discussed in Table 1. Keeping the same assumption that ports have *naive expectations*, the FOC with respect to quantity f_j^{ii} gives:[59]

[59] The second order conditions are satisfied, as $\frac{\partial^2 W_j^{ii}}{\partial (f_j^{ii})^2} = -2(840-671\alpha)/1225t < 0$ with $j = A, B$ and the cross derivatives are $\frac{\partial^2 W_j^{ii}}{\partial f_j^{ii} f_{-j}^{ii}} = 2(70-71\alpha)/1225t$ where $j = A, B$.

$$\frac{\partial W_A^{ii}}{\partial f_A^{ii}} = \frac{2}{35t}\left(5t + 10V + 2\ C_B^{S,ii} - 12\ C_A^{S,ii} - 24\ f_A^{ii} + 2\ f_B^{ii}\right)$$
$$- \frac{\alpha}{1225t}\left(355t + 1200V - 1342\ C_A^{S,ii} + 142\ C_B^{S,ii} - 1342\ f_A^{ii} + 142\ f_B^{ii}\right) = 0. \tag{A.5}$$

Similarly to the quantity competition, we assume that $\mathbf{f}^{*i} = (f_A^{*i}, f_B^{*i})$ is the solution of the single-period Bertrand game, then we have $\mathbf{f}^i = \mathbf{f}^{i*}$, where:

$$f_A^{*i} = \frac{1}{4(5005 - 7981\alpha + 3180\alpha^2)}\{[70(65t + 130V + 12C_B^{S,i} - 142C_A^{S,i})]$$
$$- (8325\ t + 23020\ V - 23872\ C_A^{S,i} + 852\ C_B^{S,i})\alpha + 53(71t + 240V - 240C_A^{S,i})\alpha^2]\}, \tag{A.6}$$

$$f_B^{*i} = \frac{1}{4(5005 - 7981\alpha + 3180\alpha^2)}\{[70(65t + 130V + 12C_A^{S,i} - 142C_B^{S,i})]$$
$$- (8325\ t + 23020\ V - 23872\ C_B^{S,i} + 852\ C_A^{S,i})\alpha + 53(71t + 240V - 240C_B^{S,i})\alpha^2]\}. \tag{A.7}$$

Next, we replace the constraint $f_{-j}^{ii} = f_{-j}^{i}$ into the FOC in (A.5) for $j = A, B$, i.e., by considering that port A assumes that port B chooses the same fee as previously set in the next period ($f_B^{ii} = f_B^i$) and port B behaves the same way. The adjustment process to the Nash Equilibrium becomes:

$$f_A^{ii} = \frac{1}{2(840 - 671\alpha)}[2(70 + 71\alpha)\ f_B^i + 70(5t + 10V + 2C_B^{S,ii} - 12C_A^{S,ii})$$
$$-\ \alpha(1200V + 355t - 1342C_A^{S,ii} + 142C_B^{S,ii})] = \phi(f_B^i),$$
$$f_B^{ii} = \frac{1}{2(840 - 671\alpha)}[2(70 + 71\alpha)\ f_A^i + 70(5t + 10V + 2C_A^{S,ii} - 12C_B^{S,ii})$$
$$-\ \alpha(1200V + 355t - 1342C_B^{S,ii} + 142C_A^{S,ii})] = \psi(f_A^i).$$

By replacing f_j^i with f_j^{*i} with $j = A, B$ in the dynamics of the adjustment process equations and solving the systems of two equations $f_A^{ii} = \phi(f_B^i)$ and $f_B^{ii} = \psi(f_A^i)$ for f_A^{ii} and f_B^{ii}, we obtain the fees in equilibrium for period $T = ii$, which are:

$$f_A^{*ii} = \frac{1}{4(3180\alpha^2 - 7981\alpha + 5005)}\{[70(65t + 130V + 12C_B^{S,ii} - 142C_A^{S,ii})] - (8325\ t + 23020\ V - 23872\ C_A^{S,ii}$$
$$+ 852\ C_B^{S,ii})\alpha + 53(71t + 240V - 240C_A^{S,ii})\alpha^2]\}, \tag{A.8}$$

$$f_B^{*ii} = \frac{1}{4\left(3180\alpha^2 - 7981\alpha - 5005\right)}\left\{\left[70\left(65t + 130V + 12C_A^{S,ii} - 142C_B^{S,ii}\right)\right] - \left(8325\,t + 23020\,V - 23872\,C_B^{S,ii}\right.\right.$$
$$\left.\left. + 852\,C_A^{S,ii}\right)\alpha + 53\left(71t + 240V - 240C_B^{S,ii}\right)\alpha^2\right]\Big\}, \tag{A.9}$$

where $C_j^{S,T}$ corresponds to the adaptation costs incurred by shippers transporting cargo through port j, $j = A, B$ at period $T = i, ii$, given by:[60]

$$C_j^{S,T} = \gamma\left[Dx\ G_1\left(\frac{Dx}{I_j}\right) - \bar{\theta}_1^j(I_j)\ I_j\right], \quad \text{if} \quad \theta_1 \le \frac{Dx}{I_j}, \quad j = A, B, \quad T = i, ii. \tag{A.10}$$

The equilibrium demands for ports at period T where $T = \{i, ii\}$ come from replacing the equilibrium fees into (A.3) and (A.4). It gives:

$$q_A^{*T} = \frac{371t\alpha^2 - (1091t + 1272V - 1356\ C_A^{S,T} + 84\ C_B^{S,T})\alpha + 12(65t + 130V - 142\ C_A^{S,T} + 12\ C_B^{S,T})}{t\ (3180\alpha^2 - 7981\alpha + 5005)}, \tag{A.11}$$

$$q_B^{*T} = \frac{371t\alpha^2 - (1091t + 1272V - 1356\ C_B^{S,T} + 84\ C_A^{S,T})\alpha + 12(65t + 130V - 142\ C_B^{S,T} + 12\ C_A^{S,T})}{t\ (3180\alpha^2 - 7981\alpha + 5005)}. \tag{A.12}$$

The quantity equilibrium for the private ports during period T, denoted by $\mathbf{q}^{*\mathbf{0T}} = (\mathbf{q}_\mathbf{A}^{*\mathbf{0T}}, \mathbf{q}_\mathbf{B}^{*\mathbf{0T}})$ comes from replacing parameter α by zero in (A.11) and (A.12), yielding:

$$q_A^{*0T} = \frac{12\left(65t + 130V - 142\,C_A^{S,T} + 12\,C_B^{S,T}\right)}{5005t} \quad \text{and} \quad q_B^{*0T} = \frac{12\left(65t + 130V - 142\,C_B^{S,T} + 12\,C_A^{S,T}\right)}{5005t},$$

[60] The expression of the adaptation costs for shippers is obtained by decomposing the *Max* function in (1).

where $C_j^{S,T}$ are the adaptation costs incurred by the shippers at port j with $j = A, B$ during period T, which in turn depend on the investment timing.

The quantities produced by the port authorities ($\alpha = 1$) at period T, denoted by $\mathbf{q}^{*\mathbf{1T}} = (\mathbf{q}_{\mathbf{A}}^{*\mathbf{1T}}, \mathbf{q}_{\mathbf{B}}^{*\mathbf{1T}})$ are given by:

$$q_A^{*1T} = \frac{5t + 24V - 29\ C_A^{S,T} + 5\ C_B^{S,T}}{17t} \quad \text{and} \quad q_B^{*1T} = \frac{5t + 24V - 29\ C_B^{S,T} + 5\ C_A^{S,T}}{17t}. \tag{A.13}$$

The procedures to obtain the adaptation investments are similar to the case of quantity competition. When the adaptation investments are made at the beginning of the first period, the fees set by the ports in the first and second period are given by Eqs. (A.6)–(A.7) and (A.8)–(A.9), respectively.

Ignoring first the constraint $\theta_1 I_j \le Dx$, the FOCs with respect to $\mathbf{I}$ for the private ports read:[61]

$$\frac{\partial W_j}{\partial I_j} = \bar{\theta}_1^j(I_j)\left[\frac{142}{143}\gamma\left(q_j^{*i} + kq_j^{*ii}\right) + (1+k)\right] - (1+k\beta) = 0, \quad \text{with} \quad j = A, B,$$

where q_j^{*i} and q_j^{*ii} are the (equilibrium) quantities obtained in Eqs. (21).

For the port authorities, the FOCs with respect to $\mathbf{I}$ are:

$$\frac{\partial W_j}{\partial I_j} = \bar{\theta}_1^j(I_j)\Bigg[\frac{\gamma}{17t}\left[(6t + 29V - 29C_j^{S,i}) + k(6t + 29V - 29C_j^{S,ii}) - \frac{t}{2}(q_j^{*i} + kq_j^{*ii}) - 3t(q_{-j}^{*i} + kq_{-j}^{*ii})\right]$$
$$+(1+k)\Bigg] - (1+k\beta) = 0,$$

where q_j^{*i} and q_j^{*ii} are the (equilibrium) quantities in (A.13). Since the port demands for both private and public ports depend on the conditional mean and CDF of θ_1, and therefore on the levels of prevention investments, we use the FOCs to characterize the optimal adaptation investments. Using the same notations as in (23), we have:

$$I_{A,1}^{*\alpha} = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m_A^{\alpha}(\mathbf{I}_1^{\alpha *})}\right]}; \quad I_{B,1}^{*\alpha} = \frac{Dx}{F_1^{-1}\left[\frac{1+k\beta}{m_B^{\alpha}(\mathbf{I}_1^{\alpha *})}\right]}, \quad \text{where} \quad \alpha = \{0, 1\},$$

where superscript α indicates the ports' ownership form, and terms $m_j^{\alpha}(\mathbf{I}_1^{\alpha *})$ with $j = A, B$ and $\alpha = 0, 1$, are defined as follows:

$$m_j^0(\mathbf{I}_1^{\alpha *}) = \frac{142}{143}\gamma(q_j^{*i} + kq_j^{*ii}) + (1+k), \quad j = A, B.$$
$$m_j^1(\mathbf{I}_1^{\alpha *}) = \frac{\gamma}{17t}\left[(6t + 29V - 29C_j^{S,i}) + k(6t + 29V - 29C_j^{S,ii}) - \frac{t}{2}(q_j^{*1i} + kq_j^{1*ii}) - 3t(q_{-j}^{*1i} + kq_{-j}^{*1ii})\right] + (1+k).$$

The condition for an interior solution consists of replacing I_1^{α} with its optimal value in the constraint $I_{j,1}^{\alpha *} \le Dx|\theta_1$, yielding:

$$\theta_1 \le F_1^{-1}\left[\frac{1+k\beta}{m_j^{\alpha}(\mathbf{I}_1^{\alpha *})}\right], \quad \forall \theta \in [0, \theta_{max}], \quad \text{where} \quad j = A, B.$$

When the investments are undertaken at the beginning of the second period, the procedures are the same as the case of quantity competition. For the privately-owned ports, i.e., when $\alpha = 0$, the first order conditions with respect to $\mathbf{I}$ give:[62]

$$\frac{\partial W_j}{\partial I_j^0} = k\ \bar{\theta}_2^j(I_j)\left(\frac{142}{143}\gamma q_j^{*ii} + 1\right) - k = 0, \quad \text{where} \quad \bar{\theta}_2^j(I_j) = \int_0^{\frac{Dx}{I_j}} \theta_2\ g_2(\theta)\ d\theta_2,$$

where $j = A, B$. For public ports, i.e., when $\alpha = 1$, the first order conditions with respect to $\mathbf{I}$ are:

$$\frac{\partial W_j}{\partial I_j^1} = k\bar{\theta}_2^j\left\{\frac{\gamma}{34}\left[\frac{2}{t}(6t + 29V) - \frac{58}{t}C_j^{S,ii} - q_j^{*ii} - 6q_{-j}^{*ii}\right] + 1\right\} - k = 0, \quad j = A, B.$$

Again, term q_j^{*ii} and $C_j^{S,ii}$ with $j = A, B$ depend on the level of adaptation investments at equilibrium. Using the same notation as in (23) with $h = 2$, we characterize the optimal levels of disaster prevention investments $\mathbf{I}_2^* = (I_{A,2}^*, I_{B,2}^*)$ by the following

[61] The second order conditions are satisfied, i.e., $\frac{\partial \Pi_j^2}{\partial I_j^2} \le 0$ for $\theta_1, g_1, q_j^{*T}, f_j^{*T} \ge 0$ with $j = A, B$ and $T = i, ii$.

[62] The second order conditions are satisfied, as $\frac{\partial \Pi_j^2}{\partial I_j^2} < 0$ when $q_j^{*ii}, g_2(\theta) > 0$ for $j = A, B$

equations:

$$I_{A,2}^{*\alpha} = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}_A^{\alpha}(\mathbf{I_2^{*\alpha}})}\right]}; \quad I_{B,2}^{*\alpha} = \frac{Dx}{F_2^{-1}\left[\frac{1}{\bar{m}_B^{\alpha}(\mathbf{I_2^{*\alpha}})}\right]}, \quad \text{where}$$

$$\bar{m}_j^0(\mathbf{I_2^{*0}}) = \frac{142}{143}\gamma q_j^{*ii} + 1, \quad \bar{m}_j^1(\mathbf{I_2^{*1}}) = \frac{\gamma}{34}\left[\frac{2}{t}(6t + 29V) - \frac{58}{t}C_j^{S,ii} - q_j^{*ii} - 6q_{-j}^{*ii}\right] + 1, \quad j = A, B.$$

The condition to be guaranteed for an interior solution at equilibrium, $I_{j,2}^* \leq Dx|\theta_2$, becomes $\theta_2 \leq F_2^{-1}[\frac{1}{\bar{m}_j^{\alpha}(\mathbf{I_2^*})}]$, $\forall\theta \in [0, \theta_{\max}]$ where $j = A, B$. The effects of each model parameter on the size of adaptation investments, ports' discounted profits and local welfare under price competition can be obtained by using the same methods as for the case for quantity competition. Specifically, we use parameter values provided in Table 2 and conduct simulation exercises. The main insights from the simulation exercises into the impacts of model parameters and information accumulation are similar to the ones under quantity competition. For the sake of clarity and to avoid repetition, the simulation results are not reported but are available upon request. However, we summarize in Table A.3 and Table A.4 the analytical results under both price and quantity competition.

Table A.3
Duopoly with Quantity Competition: Private Ports v.s. Port Authorities.

Variable	Private Ports	Public Ports
Quantities q_A^T	$\frac{2}{143t}[11(2V+t) - 24C_A^{S,T} + 2C_B^{S,T}]$	$\frac{1}{3t}(4V + t - 5C_A^{S,T} + C_B^{S,T})$
Fees f_A^T	$\frac{3}{143}[11(2V+t) - 24C_A^{S,T} + 2C_B^{S,T}]$	$-\frac{1}{12}(16V + t - 17C_A^{S,T} + C_B^{S,T})$
Early Investments $\mathbf{I}_1$	$I_{A,1}^{*0} = \frac{Dx}{F_1^{-1}[\frac{1+k\beta}{m_A^0(\mathbf{I_1^{0}}*)}]}$	$I_{A,1}^{*1} = \frac{Dx}{F_1^{-1}[\frac{1+k\beta}{m_A^1(\mathbf{I_1^{1}}*)}]}$
where	$m_A^0 = \frac{144}{143}\gamma(q_A^{*0i} + kq_A^{*0ii}) + (1+k)$	$m_A^1 = \frac{\gamma}{6t}[6t(q_A^{*1i} + kq_A^{*1ii}) - t(q_B^{*1i} + kq_B^{*1ii}) + (2V - C_B^{S,i}) + k(2V - C_B^{S,ii})] + (1+k)$
Late Investments $\mathbf{I}_2$	$I_{A,2}^{*0} = \frac{Dx}{F_2^{-1}[\frac{1}{\bar{m}_A^0(\mathbf{I_2^{*0}})}]}$	$I_{A,2}^{*1} = \frac{Dx}{F_2^{-1}[\frac{1}{\bar{m}_A^1(\mathbf{I_2^{*1}})}]}$
where	$\bar{m}_A^0 = \frac{144}{143}\gamma q_A^{*0ii} + 1$	$\bar{m}_A^1 = \frac{\gamma}{6t}(6tq_A^{*ii} - tq_B^{*1ii} + 2V - C_B^{S,ii}) + 1$

Table A.4
Duopoly with Price Competition: Private Ports v.s. Port Authorities.

Variable	Private Ports	Public Ports
Quantities q_A^T	$\frac{12}{5005t}[65(t+2V) - 142\, C_A^{S,T} + 12\, C_B^{S,T}]$	$\frac{1}{17t}(5t + 24V - 29\, C_A^{S,T} + 5\, C_B^{S,T})$
Fees f_A^T	$\frac{1}{286}[65(t+2V) + 12C_B^{S,T} - 142C_A^{S,T}]$	$-\frac{1}{68}(t + 100V - 101C_A^{S,i} + C_B^{S,i})$
Early Investments $\mathbf{I}_1$	$I_{A,1}^{*0} = \frac{Dx}{F_1^{-1}[\frac{1+k\beta}{m_A^0(\mathbf{I_1^{0}}*)}]}$	$I_{A,1}^{*1} = \frac{Dx}{F_1^{-1}[\frac{1+k\beta}{m_A^1(\mathbf{I_1^{1}}*)}]}$
where	$m_A^0 = \frac{142}{143}\gamma(q_A^{*i} + kq_A^{*ii}) + (1+k)$	$m_A^1 = \frac{\gamma}{34t}[2(6t+29V)(1+k) - 58(C_A^{S,i} + kC_A^{S,ii}) - t(q_A^{*1i} + kq_A^{*1ii})$ $- 6t(q_B^{*1i} + kq_B^{*ii})] + (1+k)$
Late Investments $\mathbf{I}_2$	$I_{A,2}^{*0} = \frac{Dx}{F_2^{-1}[\frac{1}{\bar{m}_A^0(\mathbf{I_2^{*0}})}]}$	$I_{A,2}^{*1} = \frac{Dx}{F_2^{-1}[\frac{1}{\bar{m}_A^1(\mathbf{I_2^{*1}})}]}$
where	$\bar{m}_A^0 = \frac{142}{143}\gamma q_A^{*0ii} + 1$	$\bar{m}_A^1 = \frac{\gamma}{34t}[2(6t+29V) - 58C_A^{S,ii} - tq_A^{*1ii} - 6tq_B^{*1ii}] + 1$

Appendix B. Additional Results

B.1. Simulation results for private ports when investments are made separately

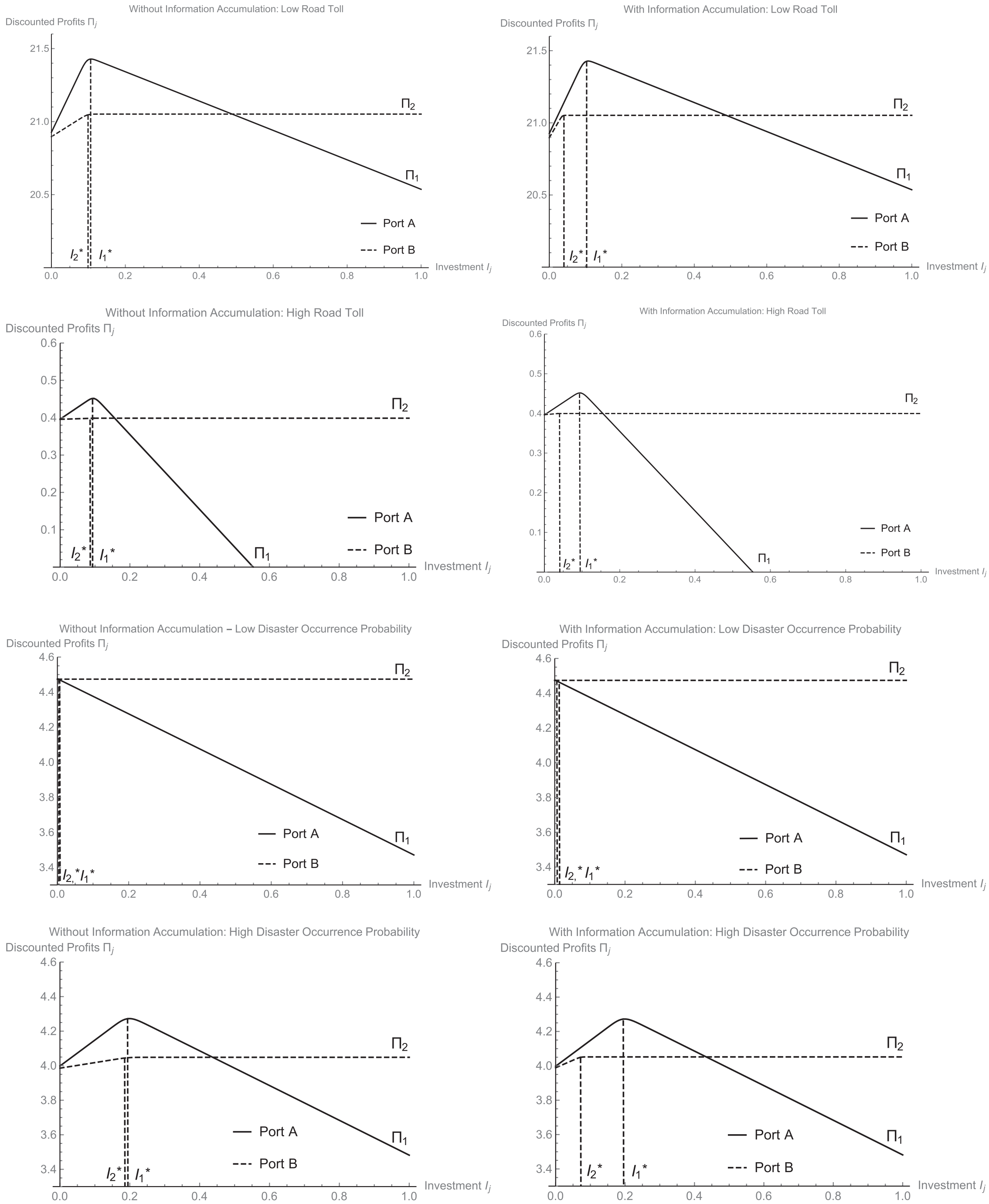

Fig. B.1. Impacts of parameters on discounted profits when the investments are chosen at different times.

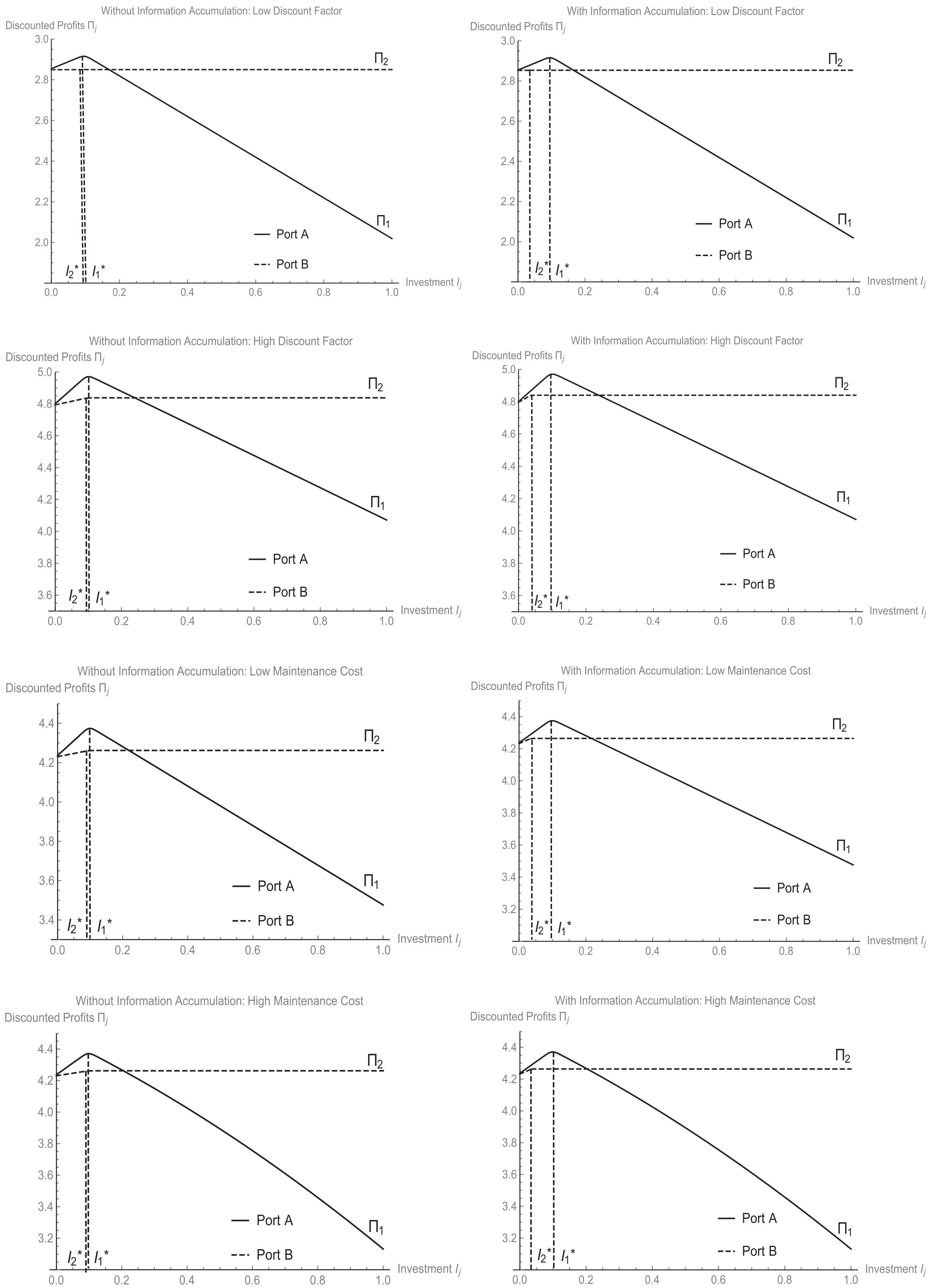

Fig. B.2. Impacts of parameters on discounted profits when the investments are chosen at different times (cont'd).

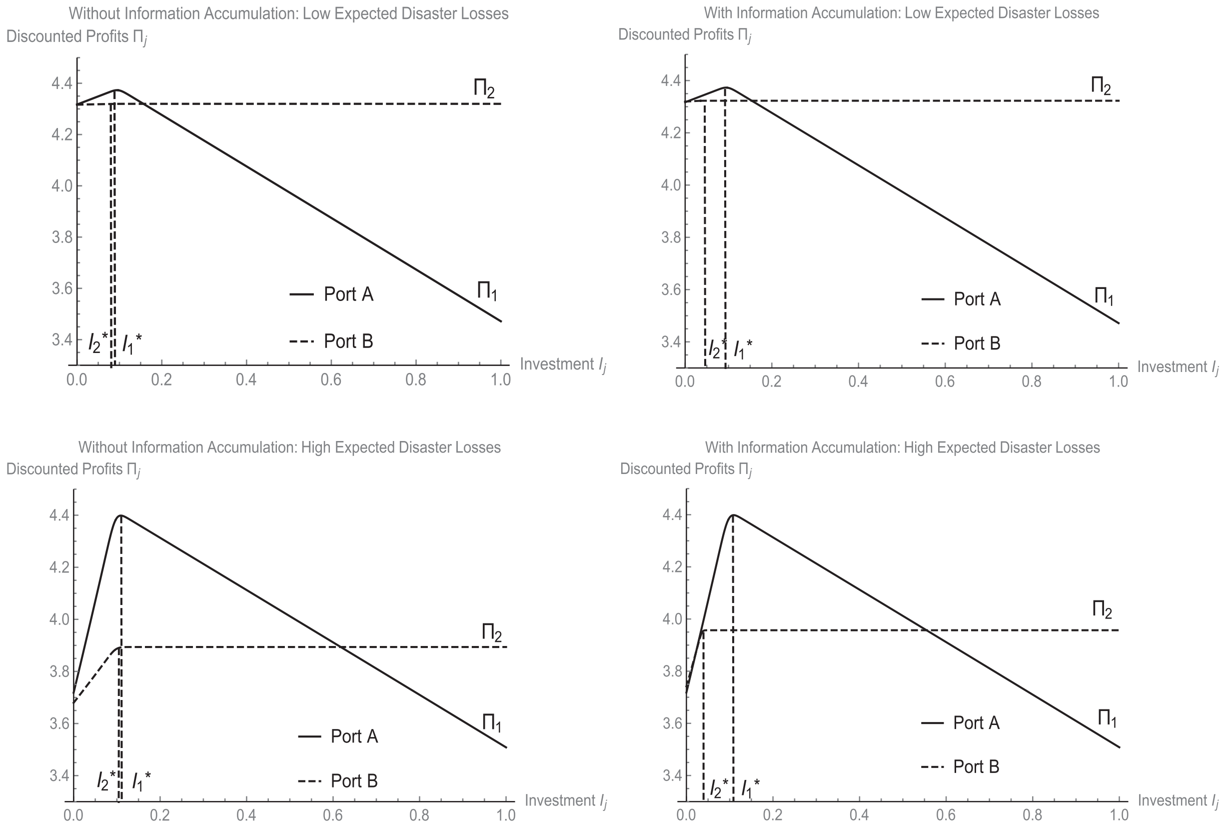

Fig. B.3. Impacts of parameters on discounted profits when the investments are chosen at different times (cont'd).

B.2. Simulation results for public ports when investments are made separately

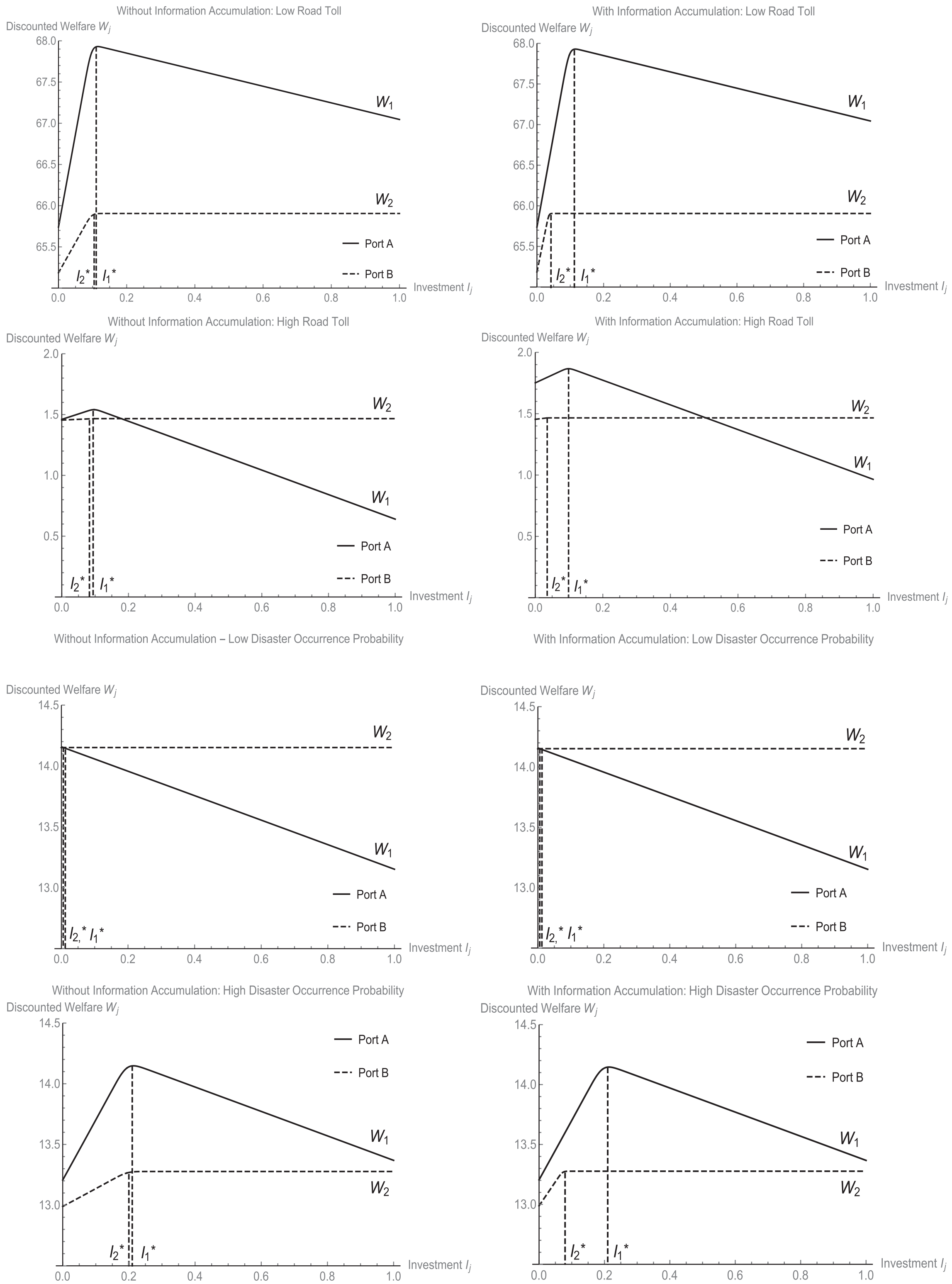

Fig. B.4. Impacts of parameters on discounted welfare when the investments are made at different times.

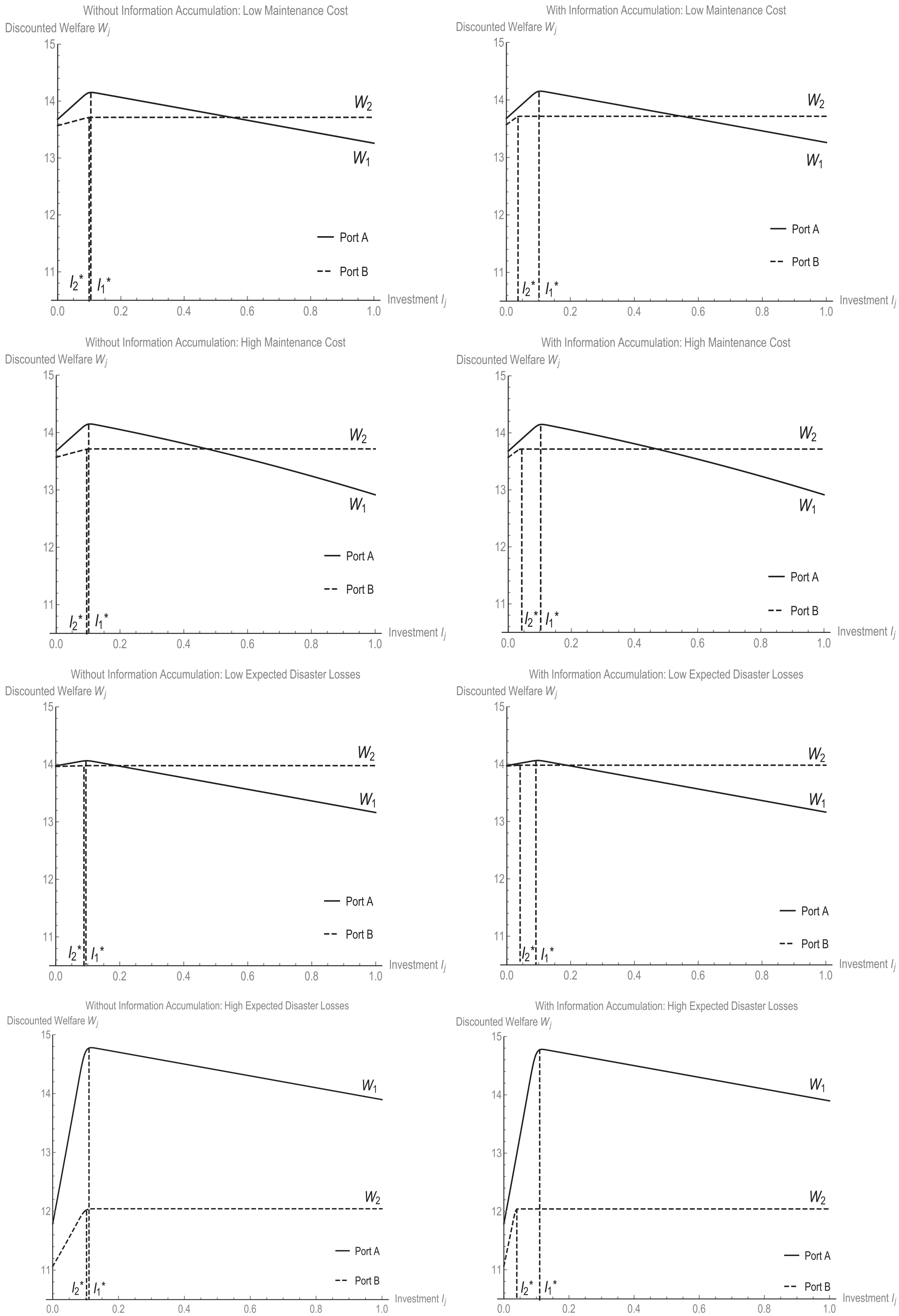

Fig. B.5. Impacts of parameters on discounted welfare when the investments are made at different times (cont'd).

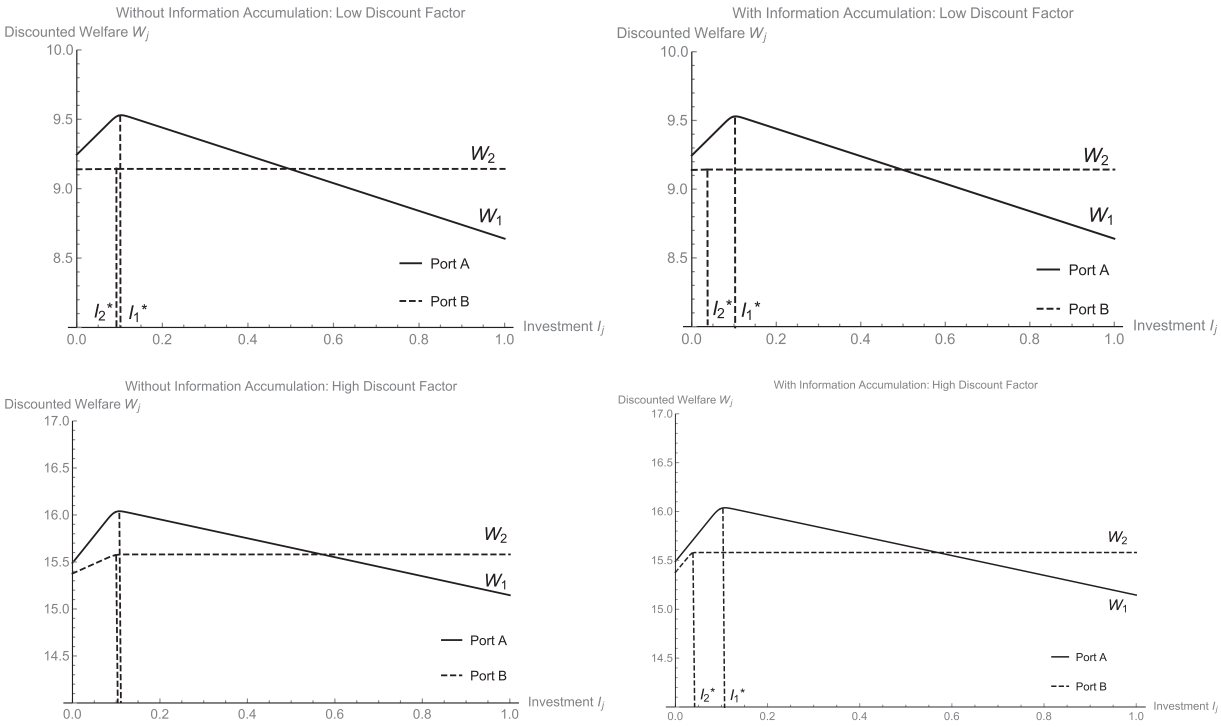

Fig. B.6. Impacts of parameters on discounted welfare when the investments are made at different times (cont'd).

B.3. Decomposition of the adaptation costs for ports C_j^i under the assumption of knightian uncertainty for disaster occurrence probability x

Suppose that $x_T > \theta_h I_j / D$, which is equivalent to assume $\theta_h < Dx_i / I_j$ for $T = i$ and $h = \{1, 2\}$. The new adaptation cost associated with early investments ($h = 1$) in the first period ($T = i$) becomes:

$$C_j^i = E_x E_\theta [I_j + Dx_i - \theta_1 I_j] = \int_{I_j \theta_1 / D}^{\bar{x}} \int_0^{Dx_i / I_j} (I_j + Dx_i - \theta_1 I_j)\ g_1(\theta_1)\ p(x_i)\ d\theta_1\ dx_i. \tag{B.1}$$

In order to solve the integrands and avoid confusion, we rename variables x_i and θ_1 in the integral functions $''y''$ and $''z''$, respectively. Then, we rewrite Eq. (B.1) as follows:

$$\begin{aligned} C_j^i &= \int_{I_j \theta_1 / D}^{\bar{x}} \left[\int_0^{Dx_i / I_j} (I_j + Dy - zI_j)\ g_1(z)\ dz \right] p(y)\ dy \\ &= \int_{I_j \theta_1 / D}^{\bar{x}} \left[I_j + Dy \int_0^{Dx_i / I_j} g_1(z)\ dz - I_j \int_0^{Dx_i / I_j} z g_1(z)\ dz \right] p(y)\ dy \\ &= \int_{I_j \theta_1 / D}^{\bar{x}} \left[I_j + Dy\ G_1\left(\frac{Dx_i}{I_j} \right) - I_j\ \bar{z}^j(I_j) \right] p(y)\ dy, \end{aligned} \tag{B.2}$$

where

$$G_1(a) = \int_0^a g_1(z)\ dz \text{ is the cdf of } g_1 \quad \text{and} \quad \bar{z}^j(I_j) = \int_0^{Dx_i / I_j} z\ g_1(z) dz$$

is the conditional mean of z. Solving the integrand in (B.2) with respect to y, we obtain:

$$\begin{aligned} C_j^i &= \left[\int_{I_j \theta_1 / D}^{\bar{x}} Dy\ G_1\left(\frac{Dx_i}{I_j} \right) p(y)\ dy + \int_{I_j \theta_1 / D}^{\bar{x}} I_j\ [1 - \bar{z}^j(I_j)]\ p(y)\ dy \right] \\ &= \left[D\ G_1\left(\frac{Dx_i}{I_j} \right) \int_{I_j \theta_1 / D}^{\bar{x}}\ y p(y)\ dy + I_j\ [1 - \bar{z}^j(I_j)] \int_{I_j \theta_1 / D}^{\bar{x}}\ p(y)\ dy \right]. \end{aligned}$$

Denoting $P(y)$ the cdf of y and $\bar{y}^j(I_j)$ the conditional mean of y when $I_j\theta_1/D < y < \bar{y}$, i.e.,

$$P(a) = \int_0^a p(y)\ dy \quad \text{and} \quad \bar{y}^j(I_j) = \int_{I_j\theta_1/D}^{\bar{y}} y\ p(y)\ dy,$$

the adaptation cost for port j becomes:

$$C_j^i = D\ G_1\left(\frac{Dx_i}{I_j}\right)\ \bar{y}^j(I_j) + I_j\ [1 - \bar{z}^j(I_j)]\left[P(\bar{x}) - P\left(\frac{I_j\theta_1}{D}\right)\right].$$

The expression for $C_j^{S,i}$ with the original variables is:

$$C_j^i = D\ \bar{\mu}_x^j(I_j)\ G_1(Dx_i/I_j) + I_j\ [1 - \bar{\theta}_1^j(I_j)]\big[P(\bar{x}) - P(I_j\theta_1/D)\big],$$

where

$$\bar{\mu}_x^j(I_j) = \int_{I_j\theta_1/D}^{\bar{x}} x\ p(x)\ dx \quad \text{and} \quad \bar{\theta}_1^j(I_j) = \int_0^{Dx_i/I_j} \theta_1\ g_1(\theta_1)d\theta_1.$$

B.4. Details of the single-Cournot competition under knightian uncertainty

In a single-Cournot game, the port authorities simultaneously choose quantities $\mathbf{q^i} = (q_A^i, q_B^i)$ so as to maximize profits. The maximization problem of port authority j reads:

$$\max_{\mathbf{q}^i} E_x[\Pi_j] = \int_x \Pi_j^i\ p(x)\ dx = \int_x \left[f_j^T(\mathbf{q}^T)\ q_j^T - C_j^T\right]p(x)\ dx, \quad \text{where} \quad j = A, B, \quad T = i, ii. \tag{B.3}$$

Inverse demand function $f_j^T(\mathbf{q}^T)$ is given by Eq. (12), i.e.,

$$f_j^T(\mathbf{q}^T) = \frac{1}{4}\big(2t + 4V - 4C_j^{S,T} - 6t\ q_j^T - t\ q_{-j}^T\big),$$

where $C_j^{S,T} = \gamma\ E[Max\{Dx_T - \theta_h I_j, 0\}]$. To simplify the notation, we use $C_j(x)$ instead of $C_j^{S,T}$. Substituting f_j^T into (B.3), we can rewrite the objective function of port authority j as follows:

$$E_x[\Pi_j] = \int_x \left[\frac{1}{4}\left[2t + 4V - 4C_j(x) - 6t\ q_j^T - t\ q_{-j}^T\right]\ q_j^T - C_j^j\right]p(x)\ dx, \quad j = A, B.$$

Using the Leibniz integral rule, we obtain the first order conditions with respect to $\mathbf{q} = (q_j, q_{-j})$, yielding:

$$\begin{aligned}
\frac{\partial E_x[\Pi_j]}{\partial q_j} &= \frac{\partial}{\partial q_j}\int_x \left[\frac{1}{4}\left[2t + 4V - 4C_j(x) - 6t\ q_j - t\ q_{-j}\right]\ q_j - C_j^j\right]p(x)\ dx \\
&= \frac{1}{4}\int_x \frac{\partial}{\partial q_j}[2t + 4V - 4C_j(x) - 6t\ q_j - t\ q_{-j}]\ q_j\ p(x)\ dx \\
&= \frac{1}{4}\int_x [2t + 4V - 4C_j(x) - 12t\ q_j - t\ q_{-j}]\ p(x)\ dx \\
&= \frac{1}{4}\int_x [(2t + 4V) - 12t\ q_j - t\ q_{-j}]\ p(x)\ dx - 4\int_x C_j(x)p(x)\ dx.
\end{aligned}$$

Denoting

$$P_j = \int_x p(x)dx, \quad \bar{C}_j(x) = \int_x C_j(x)\ p(x)\ dx \quad \text{for} \quad x > \frac{\theta_1 I_j}{D}.$$

The first order conditions with respect $\mathbf{q}$ give:

$$\frac{\partial E_x[\Pi_j]}{\partial q_j} = \frac{1}{4}\left[(2t + 4V)P_j - 12t\ q_j P_j - t\ q_{-j}P_j - 4\bar{C}_j(x)\right] = 0, \quad j = A, B. \tag{B.4}$$

Solving Eq. (B.4) for $\mathbf{q^x} = (q_A^x, q_B^x)$ leads to the solutions of the single-period maximization problem, which are given by:

$$q_j^{*Tx} = \frac{2}{143t}\left[11(2V + t) - \frac{24}{P_j}\ \bar{C}_j^{S,T}(x) + \frac{2}{P_{-j}}\ \bar{C}_{-j}^{S,T}(x)\right], \quad j = A, B, \quad j \neq -j.$$

References

Altay, N., Ramirez, A., 2010. Impact of disasters on firms in different sectors: Implications for supply chains. J. Supply Chain Manag. 46 (4), 59–80.
Auffret, P., 2003. High consumption volatility. World Bank Publications, Washington DC, USA.
Azevedo, A., Paxson, D., 2014. Developing real option game models. Eur. J. Oper. Res. 237 (3), 909–920.
Baake, P., Mitusch, K., 2007. Competition with congestible networks. J. Econ. 91 (2), 151–176.
Bae, M.J., Chew, E.P., Lee, L.H., Zhang, A., 2013. Container transshipment and port competition. Marit. Policy Manag. 40 (5), 479–494.
Balliauw, M., Kort, P.M., Zhang, A., 2019. Capacity investment decisions of two competing ports under uncertainty: A strategic real options approach. Transp. Res. Part B 122, 249–264.
Balliauw, M., Meersman, H., Van de Voorde, E., Vanelslander, T., 2018. Towards improved port capacity investment decisions under uncertainty: A real options approach. Transp. Rev. in press.
Basso, L.J., Zhang, A., 2007. Congestible facility rivalry in vertical structures. J. Urban Econ. 61 (2), 218–237.
Becker, A., Inoue, S., Fischer, M., Schwegler, B., 2012. Climate change impacts on international seaports: Knowledge, perceptions, and planning efforts among port administrators. Clim. Change 110 (1–2), 5–29.
Becker, A., Matson, P., Fischer, M., Mastrandrea, M.D., 2015. Towards seaport resilience for climate change adaptation: Stakeholder perceptions of hurricane impacts in gulfport (MS) and providence (RI). Prog. Plann. 99, 1–49.
Becker, A., Ng, A.K., McEvoy, D., Mullett, J., 2018. Implications of climate change for shipping: Ports and supply chains. Wiley Interdiscip. Rev. Clim. Change 1–34.
Becker, A.H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., Esteban, M., Mather, A., Messner, S., Naruse, S., Ng, A.K.Y., Rahmstorf, S., Savonis, M., Song, D., Stenek, V., Velegrakis, A.F., 2013. A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society. Clim. Change 120 (4), 683–695.
Belasen, A.R., Polachek, S.W., 2008. How hurricanes affect wages and employment in local labor markets. Am. Econ. Rev. 98 (2), 49–53. doi:10.1257/aer.98.2.49.
Belasen, A.R., Polachek, S.W., 2009. How disasters affect local labor markets: The effects of hurricanes in florida. J. Human Resour. 44 (1), 251–276.
Berle, Ø., Rice Jr, J.B., Asbjørnslett, B.E., 2011. Failure modes in the maritime transportation system: A functional approach to throughput vulnerability. Marit. Policy Manag. 38 (6), 605–632.
Bichou, K., Gray, R., 2005. A critical review of conventional terminology for classifying seaports. Transp. Res. Part A 39 (1), 75–92.
Bresnahan, T.F., 1981. Duopoly models with consistent conjectures. Am. Econ. Rev. 71 (5), 934–945.
Chambwera, M., Heal, G., Dubeux, C., Hallegatte, S., Leclerc, L., Markandya, A., McCarl, B.A., Mechler, R., Neumann, J., 2014. Economics of adaptation. In: Field, C., Barros, V., Dokken, D., Mach, K., Mastrandrea, M., Bilir, T., Chatterjee, M., Ebi, K., Estrada, Y., Genova, R., Girma, B., Kissel, E., Levy, MacCracken, A.N.S, Mastrandrea, P., White, L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Chang, S.E., 2000. Disasters and transport systems: Loss, recovery and competition at the port of kobe after the 1995 earthquake. J. Transp. Geogr. 8 (1), 53–65.
Chen, H.-C., Lee, T.-C., Liu, S.-M., Lee, P.T.-W., 2017. Governments' Sequential facility investments and ports' pricing under service differentiation and uncertainty. Int. J. Shipp. Transp.Logist. 9, 417–448.
Chen, H.-C., Liu, S.-M., 2016. Should ports expand their facilities under congestion and uncertainty? Transp. Res. Part B 101, 109–131.
Chevalier-Roignant, B., Flath, C.M., Huchzermeier, A., Trigeorgis, L., 2011. Strategic investment under uncertainty: A synthesis. Eur. J. Oper. Res. 215 (3), 639–650.
De Borger, B., Proost, S., 2012. Transport policy competition between governments: A selective survey of the literature. Econ. Transp. 1 (1–2), 35–48.
De Borger, B., Proost, S., Van Dender, K., 2008. Private port pricing and public investment in port and hinterland capacity. J. Transp. Econ. Policy 42 (3), 527–561.
De Borger, B., Van Dender, K., 2006. Prices, capacities and service levels in a congestible bertrand duopoly. J. Urban Econ. 60 (2), 264–283.
Dixit, A.K., Pindyck, R.S., 1994. Investment Under Uncertainty. Princeton University Press, New Jersey, USA.
Esteban, M., Webersick, C., Shibayama, T., 2009. Estimation of the economic costs of non adapting Japanese port infrastructure to a potential increase in tropical cyclone intensity. In: IOP Conference Series: Earth and Environmental Science, 6. IOP Publishing.
Federal Emergency Management Agency (FEMA), 2008. Hurricane Ike Impact Report. U.S. Department of Homeland Security, Washington, D.C.
Friedman, J.W., 1968. Reaction functions and the theory of duopoly. Rev. Econ. Stud. 35 (3), 257–272.
Friedt, F. L., 2018. The Resilience of International Trade. Working Paper, Macalester College.
Gao, Y., Driouchi, T., 2013. Incorporating knightian uncertainty into real options analysis: Using multiple-priors in the case of rail transit investment. Transp. Res. Part B 55, 23–40.
Grenadier, S.R., 1996. The strategic exercise of options: Development cascades and overbuilding in real estate markets. J. Finance 51 (5), 1653–1679.
Grenadier, S.R., 2000a. Game Choices: The Intersection of Real Options and Game Theory. Risk Books, London, UK.
Grenadier, S.R., 2000. Option exercise games: The intersection of real options and game theory. J. Appl. Corp. Finance 13 (2), 99–107.
Grenadier, S.R., 2002. Option exercise games: An application to the equilibrium investment strategies of firms. Rev. Financ. Stud. 15 (3), 691–721.
Hallstrom, D.G., Smith, V.K., 2005. Market responses to hurricanes. J. Environ. Econ. Manage. 50 (3), 541–561.
Huisman, K.J., 2013. Technology Investment: A Game Theoretic Real Options Approach, 28. Springer Science & Business Media, New York, USA.
Huisman, K.J., Kort, P.M., 2015. Strategic capacity investment under uncertainty. RAND J. Econ. 46 (2), 376–408.
Huisman, K.J., Kort, P.M., Pawlina, G., Thijssen, J.J., 2004. Strategic investment under uncertainty: Merging real options with game theory. In: Real Options. Springer, pp. 97–124.
IPCC, 2013. Summary for Policymakers. In: Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Itoh, R., 2018. Is transportation infrastructure cost recoverable under the risk of disasters? Transp. Res. Part A 118, 457–465.
Joint Legislative Committee on Performance Evaluation and Expenditure Review (PEER), 2006. The impact of Hurricane Katrina on Mississippi's commercial public ports and opportunities for expansion of the ports. Jackson, State of Mississippi.
Jones, H., Moura, F., Domingos, T., 2014. Transport infrastructure project evaluation using cost-benefit analysis. Procedia-Soc. Behav. Sci. 111, 400–409.
Keohane, R.O., Victor, D.G., 2011. The regime complex for climate change. Perspect.Polit. 9 (1), 7–23.
Knight, F.H., 1921. Risk, Uncertainty and Profit. New York: Hart, Schaffner and Marx.
Lam, J.S.L., Liu, C., Gou, X., 2017. Cyclone risk mapping for critical coastal infrastructure: Cases of east asian seaports. Ocean Coast. Manag. 141, 43–54.
Lam, J.S.L., Su, S., 2015. Disruption risks and mitigation strategies: An analysis of asian ports. Marit. Policy Manag. 42 (5), 415–435.
Leahy, J.V., 1993. Investment in competitive equilibrium: The optimality of myopic behavior. Q. J. Econ. 108 (4), 1105–1133.
Lee, C., Song, D., 2017. Ocean container transport in global supply chains: Overview and research opportunities. Transp. Res. Part B 95, 442–474.
Lempert, R. J., Sriver, R. L., Keller, K., 2012. Characterizing uncertain sea level rise projections to support investment decisions. Public Interest Energy Research Program White Paper, no. CEC-500-2012-056.
Levy, H., 2015. Stochastic Dominance: Investment Decision Making Under Uncertainty. Springer Science & Business, New York, USA.
McClearn, M., 2018. For Port of Vancouver, underestimating Pacific sea-level rises could come at a high price. Technical Report. The Globe and Mail. Published on May 5, 2018.

Min, S.-K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature 470 (7334), 378.
Mu, J.E., McCarl, B.A., Wein, A.M., 2013. Adaptation to climate change: Changes in farmland use and stocking rate in the US. Mitigat. Adapt. Strateg. Global Change 18 (6), 713–730.
Ng, A., Liu, J., 2014. Port-Focal Logistics and Global Supply Chains. Palgrave Macmillan, New York, USA.
Ng, A.K., Becker, A., Fischer, M., 2013. A Theoretical Discussion on Climate Change, Port Adaptation Strategies and Institutions. In: Proceedings of the Canadian Transportation Research Forum, Halifax, NS, Canada, pp. 10–12.
Ng, A.K.Y., Becker, A., Cahoon, S., Chen, S., Earl, P., Yang, Z., 2015. Climate Change and Adaptation Planning for Ports. Routledge, London, UK and New York, USA.
Nicholls, R., Brown, S., Hanson, S., Hinkel, J., 2010. Economics of coastal zone adaptation to climate change. Technical Report. World Bank Discussion Papers, 10. International Bank for Reconstruction and Development/World Bank. Washington, DC, USA, 2010.
Nicholls, R. J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Château, J., Muir-Wood, R., 2008. Ranking port cities with high exposure and vulnerability to climate extremes: Exposure estimates. OECD Environment Working Papers, No. 1, OECD Publishing, Paris, doi:10.1787/011766488208.
Nishimura, K.G., Ozaki, H., 2007. Irreversible investment and knightian uncertainty. J. Econ. Theory 136 (1), 668–694.
Niu, Y., Zhou, L., Zou, Z., 2019. A model of capacity choice under knightian uncertainty. Econ. Lett. 174, 189–194.
NOAA, 2018. U.S. Billion-Dollar Weather and Climate Disasters. National Centers for Environmental Information (NCEI), Asheville, North Carolina. https://www.ncdc.noaa.gov/billions/.
Odgaard, T., Kelly, C. E., Laird, J., 2006. Current practice in project appraisal in Europe. Deliverable 1 of the HEATCO project. http://eprints.whiterose.ac.uk/2502/.
OECD, 2016. Adapting transport to climate change and extreme weather: Implications for infrastructure owners and network managers. Technical Report. Discussion report of International Transport Forum, OECD, Paris, France.
Okuguchi, K., 2013. Expectations and Stability in Oligopoly Models, 138. Springer Science & Business Media, Springer-Verlag Berlin, Heidelberg and New York.
Paul, J.A., Maloni, M.J., 2010. Modeling the effects of port disasters. Marit. Econ. Logist. 12 (2), 127–146.
Port of Tokyo, 2009. Disaster prevention at the port of Tokyo. Accessed on December 22, 2018. http://www.kouwan.metro.tokyo.jp/english/portoftokyo2009/pdfimge/p35-36.pdf.
Santella, N., Steinberg, L.J., Sengul, H., 2010. Petroleum and hazardous material releases from industrial facilities associated with hurricane katrina. Risk Anal. 30 (4), 635–649.
Smit, H.T., 2003. Infrastructure investment as a real options game: The case of european airport expansion. Financ. Manag. 27–57.
Smit, H.T., Ankum, L., 1993. A real options and game-theoretic approach to corporate investment strategy under competition. Financ. Manag. 241–250.
Smit, H.T., Trigeorgis, L., 2004. Quantifying the strategic option value of technology investments. Montreal: 8th Annual International Real Options Theory.
Smythe, T.C., 2013. Assessing the Impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime Responders and Response Infrastructure. Natural Hazards Center, University of Colorado, Boulder, USA doi:10.7282/T30R9MMM.
Stern, N.H., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, UK.
Van Dender, K., 2005. Duopoly prices under congested access. J. Reg. Sci. 45 (2), 343–362.
Wan, Y., Zhang, A., 2013. Urban road congestion and seaport competition. J. Transp. Econ. Policy 47 (1), 55–70.
Wan, Y., Zhang, A., Li, K.X., 2018. Port competition with accessibility and congestion: A theoretical framework and literature review on empirical studies. Marit. Policy Manag. 45 (2), 239–259.
Wang, K., Zhang, A., 2018. Climate change, natural disasters and adaptation investments: Inter-and intra-port competition and cooperation. Transp. Res. Part B 117, 158–189.
Williams, J.T., 1993. Equilibrium and options on real assets. Rev. Financ Stud. 6 (4), 825–850.
Xiao, Y., 2011. Local economic impacts of natural disasters. J. Reg. Sci. 51 (4), 804–820.
Xiao, Y., Fu, X., Ng, A.K., Zhang, A., 2015. Port investments on coastal and marine disasters prevention: Economic modeling and implications. Transp. Res. Part B 78, 202–221.
Xiao, Y., Fu, X., Zhang, A., 2013. Demand uncertainty and airport capacity choice. Transpo. Res. Part B 57, 91–104.
Zhang, A., 2009. The impact of hinterland access conditions on rivalry between ports, in: Port competition and hinterland connections. International Transport Forum, OECD, Paris, France, pages 129–160.
Zhang, A., Zhang, Y., 2006. Airport capacity and congestion when carriers have market power. J. Urban Econ. 60 (2), 229–247.